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LAMINATED PLASTICS IN CHEMICAL EQUIPMENT  
AND PIPELINES

A. A. Shevchenko, et al

Army Foreign Science and Technology Center  
Charlottesville, Virginia

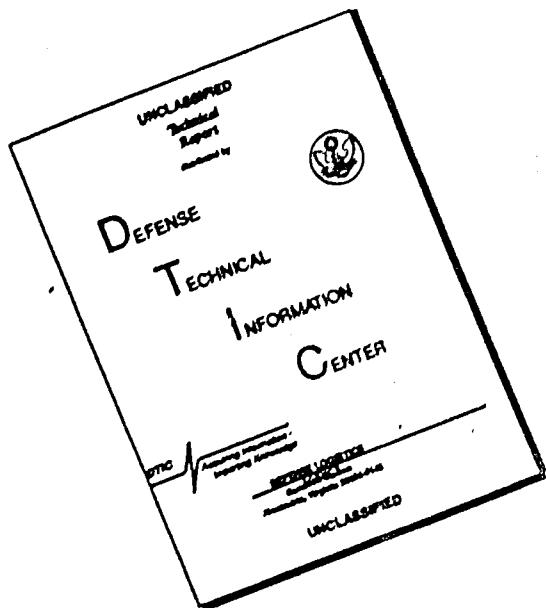
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by

A. A. Shevchenko and P. V. Vlasov

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<p>This book gives a classification and nomenclature of laminated materials, their physicomechanical characteristics, and their stability in corrosive media. Basic information on the failure mechanism of laminated plastics is presented. Methods of testing laminated plastics for corrosive stability, longevity, and creep are set forth. Methods of calculating and designing chemical equipment and pipelines made of laminated plastics are given. The book is written for designers of chemical equipment and engineering technicians in the chemical industry. Since there is a lack of data on the variation of the strength characteristics of laminated plastics in contact with chemically corrosive media in typical chemical processing conditions, the systematized calculation materials given in the book as well as methods for obtaining required data on strength and other characteristics of laminated plastics are intended to partially fill this gap and promote their broad introduction into sectors of the chemical industry and machine building.</p>		

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<b>Chapter Four [Continued]</b>	
Calculation of the Strength of Cylindrical Pressure Vessels Made of Glass-Reinforced Plastics With Helical Lay-up of Reinforcing Material	116
Strength Calculations of Chemical Equipment and Piping Made of Glass-Reinforced Plastics by the Method of Approximations	136
Simplified Method of Calculating Shells Made of Glass-Reinforced Plastics	138
Estimate of the Longevity of Pressure Piping Made of Glass-Reinforced Plastics With Allowance for a Disruption of Gas-tightness	140
<b>Chapter Five. Technological Features of the Fabrication     of Equipment and Pipelines</b>	158
Methods of Fabricating Large-Size Articles	158
Choice of Starting Material	165
Use of Combinations of Reinforced Plastics and Other Materials in Making Equipment	169
Fundamental Principles in Safety Techniques, Industrial Hygiene, and Fire Prevention	171
Quality Control	173
<b>Chapter Six. Piping, Equipment, and Pipelines</b>	176
Technical and Operating Characteristics of Piping Made of Glass-Reinforced Plastics	176
Shaped Pipeline Parts	188
Basic Rules in the Assembly, Testing, and Operations of Pipelines	189
Compensation of Thermal Elongations of Pipelines	193
<b>Chapter Seven. Methods of Connecting Structural     Members of Equipment and Pipelines</b>	196
<b>Chapter Eight. Examples of Equipment and Pipelines</b>	201
Made of Reinforced Plastics	201
Equipment Made of Glass-Reinforced Plastics	201
Design Execution of Chemical Equipment Made of Glass-Reinforced Plastics	201
Use of Equipment	203
Gas Ducts, Ventilators, and Smokestacks	208
Experience in Using Glass-Reinforced Plastic Piping	210
<b>Chapter Nine. Technical-Economic Effectiveness of     the Application of Glass-Reinforced Plastics in         Chemical Machine Building</b>	216
Conclusions	223
References	225

#### AUTHORS' ABSTRACT

A. A. Shevchenko and P. V. Vlasov. Sloistyye Plastiki v Khimicheskikh Apparatakh i Truboprovodakh (Laminated Plastics in Chemical Equipment and Pipelines), Moscow, "Mashinostroyeniye" Publishing House, 1971, 208 pp.

The book gives a classification and nomenclature of laminated materials, their physicomechanical characteristics, and their stability in corrosive media. Basic information on the failure mechanism of laminated plastics is presented. Methods of testing laminated plastics for corrosive stability, longevity, and creep are set forth.

Methods of calculating and designing chemical equipment and pipelines made of laminated plastics are given.

The book is written for designers of chemical equipment and engineering technicians in the chemical industry.

41 tables, 90 illustrations, and 105 bibliographic references.

## INTRODUCTION

At the present time, plastics are widely used in technology, mainly in the machine building industries: aviation, motor vehicle building, shipbuilding, machine building, and so on. Several structural plastics have been developed, for example, new types of glass-reinforced plastics, fluoroplastics, polypropylene, and polyformaldehyde marked by an array of valuable properties.

With the use of plastics and other nonmetallic materials in the chemical industry, it was found possible to carry out processes of chlorination, bromination, and several others, and also synthesis and production of several organochlorine products and synthetic alcohols in the chemical industry. In several cases, use of plastics has meant the production of ultra-pure products. This is vital to the pharmaceutical and food industries, and for the production of chemical reagents and ultra-pure substances.

High chemical resistance to acids, alkalis, salt solutions, oils, petroleum products, and other reagents, and good strength characteristics open up broad prospects for plastics in chemical and petroleum machine building.

Most plastics, exhibiting high specific strength, often surpassing the specific strength of metals, have inadequate rigidity and mechanical strength, which limits the possibility of their use in pressure structures.

These disadvantages can be eliminated if synthetic resins are reinforced with fibers.

Glass-reinforced plastics are being widely introduced into chemical and petroleum equipment making.

This is due to their high chemical stability, low density, mechanical strength in tension, thermostability, and heat resistance.

However, there are not enough data on the variation of the strength characteristics of laminated plastics in contact with chemically corrosive media in conditions typical of chemical processing (integrated and autonomous exposure to load, temperature, and media in time).

The systematized calculation materials given in the book as well as methods for obtaining required data on strength and other characteristics of laminated plastics are intended to partially fill this gap and promote their broad introduction into sectors of the chemical industry and machine building.

## CHAPTER ONE

### BACKGROUND INFORMATION ON CHEMICAL EQUIPMENT, PIPELINES, AND REINFORCED PLASTICS

#### Operation of Chemical Equipment and Pipelines

Chemical equipment differs from machinery and equipment in other industries by its great diversity of design execution and by stiffened requirements on its reliability stemming from operating conditions.

The reliability of chemical equipment and pipelines is characterized by mechanical strength, rigidity, stability, longevity, and gas-tightness.

The strength of plastics equipment depends on its service time.

The longevity of chemical equipment is determined mainly by corrosion, which causes diminished mechanical strength of the material of which the article is made. Most chemical equipment and pipelines must be gas-tight. High gas-tightness is requisite for equipment operating at pressure or processing toxic, caustic, flammable, and explosive substances. Chemical equipment includes large numbers of connecting parts (connecting pieces and fittings) required for the operation and connecting of monitoring instrumentation and regulatory devices.

The diversity of the design executions of chemical equipment is due to the varied technological processes employing the equipment, the forces acting on the equipment, manufacturing methods, and operating requirements.

The layout and main dimensions of equipment (length, diameter, and cross-sectional area) are determined mainly by the technological process and the required capacity. Here the nature of the process being carried out (hydraulic, thermal, diffusional, or chemical), the rate of the process and the method of its execution (batch or continuous), the state of aggregation of the substances being processed, the thermodynamic conditions (pressure, temperature, and concentration of the substances being processed), corrosiveness of the materials, purity of the end product, and so on -- all these factors must be taken into account.

The dimensions of equipment and pipelines are determined with allowance for the chemical properties of the material, the nature of the loading, and the rate and degree of corrosion.

Operational requirements are also taken into account in the designs of equipment and their installation (flanges, hatches, covers, inspection windows, and so on).

As experience has shown, the form of most chemical equipment (cylindrical, conical, or spherical) and pipelines is favorable for their production from reinforced plastics. In most equipment, the main working space is bounded by a cylindrical shell or by cylindrical sheet-metal drums; the covers are made spherical, elliptical, or conical. These articles can be made of reinforced plastics by using the methods of winding, molding, or contact molding.

Vessels for processing purposes and storing liquid, solid, and gaseous products are the most widespread in the chemical industry. For simplification and lower manufacturing costs, the components of vessels are given the simplest geometrical shapes -- cylindrical, spherical, and conical. The bodies of many vessels are represented by a combination of these simplest forms.

The spherical form is the most suitable from the standpoint of economy of material and the uniform distribution of the induced stresses. The fabrication of spherical shells from metal is complicated and expensive. Using reinforced plastics goes far to simplify the technology of making cylindrical and spherical shells. The weight of spherical and cylindrical tanks for corrosive liquids and gases is significantly reduced when this kind of material is used in making the tanks.

Flat-walled storage vessels are used much less often than vessels bounded by surfaces of revolution.

A large group of storage vessels is used in the chemical industry for service under atmospheric pressure. This category includes equipment operating at a gage pressure of not more than  $0.7 \text{ kg/cm}^2$ . Cylindrical and oblong tanks containing corrosive media used at low pressures are also best manufactured prefabricated from reinforced plastics with cemented connections. Foreign practice furnishes examples of the fabrication of large-capacity tanks in one-piece form and prefabricated from reinforced plastics directly at the site of equipment installation. Usually methods of winding and contact molding are used for these purposes. Reactors made of reinforced plastics intended for service under internal pressure can be made in the one-piece form or with a minimum number of connections.

Column equipment intended for diffusional processes such as absorption, desorption, fractionation, and the purification, cooling, and humidifying of gases are very common in the chemical industry. Columns often operate under internal pressure. The height of a column exceeds its

transverse dimensions by several times. The shape of the cross section is a circle, but sometimes a square or a polygon. Liquid and gas pass through a column in a countercurrent manner. In column equipment the corrosive liquid is in the dispersed state, which favors corrosion processes. Fabrication of column equipment using reinforced plastics greatly reduces their weight and simplifies the design of foundations. Column equipment can be installed from standard plastic shells with the use of jointed or permanent (cemented) connections.

Hoppers, tanks, plates and frames of filter presses, sectors of disc filters, distributor heads, and blankets of vacuum filters, pumps, shells of compressor stations, covers of centrifuges, gas tanks, mixers, and so on can be made of reinforced plastics in the chemical industry.

Pipelines, air ducts, and lengthy ventilation gas ducts whose service has special features, are very widely used in the chemical industry. Therefore, the main requirements imposed on them are as follows:

adequate gas-tightness at working pressures and variable temperatures;

stability to corrosive media;

minimum linear and drag values that can lead to the crystallization of the substances being conveyed;

the possibility and convenience of replacing defective parts and making repairs; and

minor temperature stresses with a minimum number of temperature compensators.

As we can see, satisfying these requirements depends to a large extent on the piping material. The number of examples of using reinforced plastics for the fabrication of piping and gas ducts in the chemical industry is growing year by year. This is due to the fact that reinforced plastics permits simplification in the fabrication of piping and an increase in its longevity.

#### Main Requirements on Structural Materials

In selecting structural materials for the manufacture of chemical equipment and piping, the following properties are taken into account: strength characteristics, heat resistance, chemical stability, and physical and processing characteristics. Choice of material is determined by the service conditions of the equipment -- temperature, pressure, and concentration of the materials being processed.

The cost of the material itself does not yet characterize the material from the standpoint of the economic soundness of its use. Here the longevity of equipment fabricated using a given material must be taken into account.

The main requirement for material to be used in making chemical equipment and pipelines in most cases is resistance to corrosive media.

The chemical resistance of plastics is estimated according to GOST [State Standard] 12020-66, and this standard states that the numerical characteristics of the chemical resistance of plastics are as follows: change in the weight of specimens and in their linear dimensions and in their mechanical properties (yield stress in tension, relative elongation at yield, flexural strength, impact toughness, and hardness).

Structural material must have high chemical resistance since corrosion products can promote side reactions; when this takes place, the yield of the main product is reduced and its quality is lowered.

Currently, cast iron and steel are the most common materials in the building of chemical equipment. Extensive use in chemical equipment making is made of alkali-resistant, high-strength, wrought and high-silicon iron, and also high-alloy chromium-nickel steel exhibiting high corrosion resistance to many corrosive media.

Of the nonferrous metals, aluminum, copper, nickel, lead, titanium, and tantalum are used in chemical equipment making.

Nonmetallic materials of inorganic (granite, andesite, glass, and ceramics) and of organic (wood, rubber, and plastics) origin are also used as structural materials.

Compared with metals, plastics are lighter in weight, sometimes higher in specific strength, with good processing properties, and -- particularly important -- high chemical resistance and low cost. The rational use and wide introduction of plastics into chemical equipment making will afford vast monetary savings and in many cases decisively solve equipment corrosion problems.

Reinforced plastics (polyethylene, polypropylene, and polyfluoroethylenes) are the most promising materials for the needs of chemical equipment.

Use of plastics in many cases will permit modification of the design of chemical equipment owing to the diversity of plastics processing techniques. Equipment items made by different techniques will differ in design, even if intended to perform the same function. For example, a reactor is much easier to make in one piece from glass-reinforced plastics (winding method) than by fitting together cast-iron members.

The designer must often allow for the nature of the corrosion failure of material when making strength calculations for chemical equipment. In addition, he must know the permeability of the material under given working conditions of the concentration of the corrosive medium, temperature, and pressure.

Generally speaking, structural reinforced plastics that are resistant and highly resistant to corrosive media are used in fabricating chemical equipment. Reduced-resistant plastics are used in exceptional cases when -- for technical and economic reasons -- the desirability of their use in place of expensive and short-supply materials is obvious. In selecting structural reinforced materials for equipment serving under pressure and at low and high temperatures, it must be considered that the mechanical properties of plastics vary widely as a function of temperature. As a rule, the brittleness of plastics rises at low temperatures, but creep increases and strength diminishes at high temperatures.

Data from long-term tests of materials in service conditions must be used in making calculations for chemical equipment to be built of reinforced plastics. In calculating the strength of equipment continually functioning at high temperatures, the allowable stress is determined with respect to a standard creep limit for the low-term strength.

When selecting reinforced plastics for chemical equipment, technical and economic considerations must also be borne in mind: the technology of making the equipment, the supply-status and costs of the material, the availability of standards, and the degree to which industry has mastered the material. The developed equipment design must not only be technically advanced, measuring up to the demands of present-day machine building, but also technologically sound in manufacture and economical.

Cementing is the main method of executing permanent connections of reinforced materials in the present-day technology of chemical equipment making. Good cementability of materials under normal conditions is one of the chief and necessary conditions governing their suitability for a design.

Thus, considering the individualized and low-series-production status of chemical equipment fabrication, when this equipment is being designed, reinforced materials must meet the following principal requirements:

adequate chemical resistance in a corrosive medium with specified parameters of its concentration at the temperatures and loads of the given industrial process;

adequate mechanical strength, rigidity, and gas-tightness for given parameters of the industrial process, allowing for service conditions when different kinds of additional loads act on the equipment (sagging due to its own weight, wind load, and so on);

good cementability with high mechanical properties of the cemented union and resistance in corrosive media;

economy of manufacturing and operation; and

the possibility of obtaining articles with maximum overall dimensions using simple and inexpensive rigging.

### Properties of Reinforced Plastics

Reinforced plastics are composite materials consisting of synthetic resins and reinforcing fibers. As the reinforcing materials, use can be made of various fibers, for example, cotton, silk, synthetic, asbestos, glass, and textile materials (fabrics with different weaves, canvas, roving, and tape), and also nonfabric reinforcing materials in the form of laps and mats.

The reinforcement imparts strength and stiffness to the system, and the polymeric binder imparts monolithicity to the composite material, its moldability, and affords anticorrosion and other properties.

The diversity of polymeric binders, the potentialities of their combinations, the availability of various reinforcing fibers and methods of their preliminary treatment, the variety of the techniques of fabricating composites and processing them, and the possibility of varying the ratio of constituents -- all this affords a practically unlimited range of materials with wholly distinct properties.

Not every reinforced plastic can be used in making chemical equipment. The suitability of a material is determined mainly by the properties of the binder -- the synthetic resin.

Increased requirements on the chemical resistance of the binder are due to the fact that it affords the monolithicity of the material, its density and impermeability, and the protection of the reinforcement against contact with the medium.

At the present time, there is no rigorous and unique classification of reinforced plastics. For example, glass-reinforced plastics have different names in the literature: strengthened plastics, resins reinforced with glass fibers, and so on. In principle, reinforced plastics could be classified only by the nature of the reinforcing fibers, for example, glass fiber plastics -- glass-reinforced plastics; plastics reinforced with cotton fibers -- textolites; plastics reinforced with asbestos fibers -- asbestosplastics; and so on.

Reinforcing fibers. Various fibers are used as reinforcement for reinforced plastics: asbestos, cotton, jute, glass, organic (synthetic), and even metallic.

TABLE 1. PHYSICOMECHANICAL INDICATORS OF REINFORCING FIBERS

I Показатели	2 Значения показателей для волокна							
	кварцевого 3	стеклянного (E-стекло) 4	асбестового 5	льняного 6	хлопчато- бумажного 7	хрифели- таполозого 8	высокопро- чного вискоз- ного 9	высокопро- чного нейлона 10
II Кратковременная статическая прочность при растяжении в кг/см <sup>2</sup>	250 000	35 000	14 000	7000	4760	9100	7500	7000
12 Модуль упругости в кг/см <sup>2</sup>	7,0·10 <sup>4</sup>	7,5·10 <sup>4</sup>	1,7·10 <sup>4</sup>	1,0·10 <sup>4</sup>	7,7·10 <sup>4</sup>	7,85·10 <sup>4</sup>	8,7·10 <sup>4</sup>	5,6·10 <sup>4</sup>
13 Плотность в г/см <sup>3</sup>	2,6	2,5	2,5	1,5	1,5	1,3—1,4	1,3	1,2

KEY: 1 -- Indicators

2 -- Values of indicators for fibers listed below

3 -- quartz

4 -- glass (E-glass)

5 -- asbestos

6 -- flax

7 -- cotton

8 -- kraft-cellulose

9 -- high-strength viscose

10 -- high-strength nylon

11 -- Short-term static strength in tension,

kg/cm<sup>2</sup>

12 -- Modulus of elasticity in kg/cm<sup>2</sup>

13 -- Density in g/cm<sup>3</sup>

Physicomechanical properties of several fibers at room temperatures are given in Table 1 [34]. In discussing the chemical stability of fibers in general, it must be borne in mind that as fiber dimension is decreased, active fiber surface area is increased, while the chemical resistance of the fiber is reduced. For example, the chemical resistance of glass fibers is much lower than the chemical stability of monolithic glass. On the other hand, as the fiber diameter is reduced, fiber strength rises.

Asbestos fibers behave differently, depending on their chemical composition. Anthophyllite, chrysotile, and amphibole fibers are used as reinforcing material for plastics. Anthophyllite asbestos is used in making acid-resistant grades of faolite and other acid-resistant plastics. First the anthophyllite asbestos is freed of its soluble fraction by treating it with hydrochloric acid, followed by washing and drying. When chrysotile

asbestos is used, materials with diminished acid resistance but with enhanced physicomechanical indicators are obtained.

High-grade thin textile fabrics prepared from cotton and silk fibers are used in making textolites.

These fibers are considerably inferior to all other types of reinforcement as to their chemical resistance. They are chemically resistant only in neutral, weakly acidic, and weakly alkaline media.

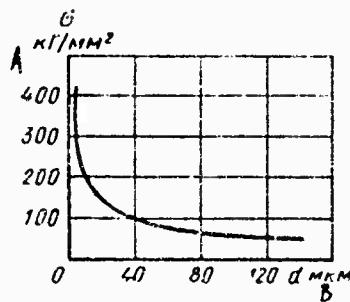


Fig. 1. Dependence of ultimate strength  $\sigma$  in tension of glass fiber on its diameter  $d$   
KEY: A --  $\sigma$ , kg/mm<sup>2</sup>  
B --  $d$ , microns

In fabricating equipment using plastics where cotton and silk fabrics are used as the reinforcement, main emphasis must be placed on protecting fibers against contact with the medium.

Glass fibers compared with other fibers show great advantages: high strength, high modulus of elasticity, low hygroscopicity, good chemical resistance, nonflammability, nondecayability, and so on.

The strength of glass fiber depends on its chemical composition, diameter, and degree of drawing. Some researchers [20] attribute the high strength of glass factor to a scale factor. As the glass fiber diameter is reduced, the number of microcracks and other surface defects becomes smaller (Fig. 1).

Recently it was established that it is not only fiber diameter that affects fiber strength, but also the degree of drawing: high strength was found for fibers with maximum plastic deformation, and -- on the other hand -- identical strength values have been obtained for fibers with varying diameters, but with an identical degree of drawing [6].

The chemical resistance of glass-reinforced plastics increases with fiber diameter. So, much interest lies in the possibility of raising the mechanical strength of large-diameter glass fibers (and along with this, the strength of glass-reinforced plastics) by increasing the degree of drawing.

The chemical resistance of glass fibers is determined by their composition. The chemical composition of glass and, in particular, its content of acidic or alkaline oxides is chosen in relation to the kind of corrosive reagent acting on the glass.

Monolithic glass is practically resistant to all substances, except for hydrofluoric acid and concentrated solutions of caustic alkalies. Owing to the greatly developed surface area, the chemical resistance of glass fibers is much lower than for monolithic glass. Therefore, the chemical composition of the charge used in making glass fibers takes on paramount importance. Additionally, it affects also the mechanical strength of glass fibers. The strength of alkaline-composition glass fibers is 20 percent below the strength of nonalkaline-composition glass fibers (content of alkaline oxides not more than 2 percent). When moisture is adsorbed on the surfaces of alkaline fibers, alkalis are formed, intensifying fiber failure. The resistance of glass fabric made with nonalkaline glass in acids is unsatisfactory. To illustrate, in 15 percent sulfuric acid at 95-98° C, nonalkaline glass fibers fail in 40 days. The weight loss is more than 30 percent.

TABLE 2. RESULTS OF TESTING GLASS-REINFORCED PLASTICS  
BASED ON FL-1 RESIN AND GLASS FABRIC WITH ALKALINE AND  
NONALKALINE COMPOSITION

1 Стеклопластик на основе волокон	Исходный предел проч- ности в кг/см <sup>2</sup> 2	Начальная масса об- разца в г 3	Концентра- ция серной кислоты в % 4	5 Изменение в %		7 массы
				пропе- ла 6	про- сто- сти	
Щелочного 8	1670	16,8119	3	-1,8	3,10	
Бесщелочного 9	2440	18,2612	3	-24,2	2,13	
Щелочного 8	1670	16,6856	30	-18,85	3,97	
Бесщелочного 9	2440	18,2258	30	-29,1	1,8	
Щелочного 8	1670	17,1535	60	-25,7	2,46	
Бесщелочного 9	2440	18,3463	60	-42,6	1,26	

KEY: [on following page]

KEY /to TABLE 2 displayed on preceding page/

- 1 -- Fiber-based glass-reinforced plastic
- 2 -- Initial ultimate strength in kg/cm<sup>2</sup>
- 3 -- Initial weight of specimen in g
- 4 -- Sulfuric acid concentration in %
- 5 -- Variation in %
- 6 -- of ultimate strength
- 7 -- of weight
- 8 -- Alkaline
- 9 -- Nonalkaline

Table 2 gives comparative data of the chemical resistance of glass-reinforced plastics based on FL-1 furan resin with alkaline and nonalkaline glass fabric in 3, 30, and 60 percent sulfuric acid solutions at 60° C (exposure time -- 720 hours). As we can see, alkaline glass is more chemically resistant under these conditions than nonalkaline glass, since the reduction in strength after exposure to sulfuric acid is less for the glass-reinforced plastics based on alkaline glass.

In selecting glass fibers, one must remember that under conditions of prolonged loading of glass-reinforced plastics in corrosive environments at high temperatures, the best results are obtained when nonalkaline glass fibers are used.

Glass fibers are hydrophilic, so in designing chemical equipment to be made of glass-reinforced plastics, it is vital to know their behavior in a wet environment. Fibers made of alkaline glass fail when exposed to water due to the formation of caustic alkalis from the oxides of alkali and alkaline-earth metals. Upon prolonged exposure to loading in a wet environment, glass fiber is reduced in strength, regardless of its chemical composition.

Because microscopic defects (cracks) are always present on the surfaces of glass fibers, when immersed in a surface-active medium (water), cracks and local stresses grow, ultimately leading to fiber failure.

In gaseous environments, in the absence of dropwise moisture condensation, fatigue failure and elastic aftereffects caused by the absorption of moisture are precluded, and the choice of the chemical composition of the glass used in making the reinforcing fibers is wholly determined by their inertness to the given environment and by requirements of structural strength.

By using fabrics with different weaves, the properties of reinforced plastics can be modified. It must -- however -- be borne in mind that any textile processing of fibers in principle worsens fiber properties, and while the order of filament weaving into yarns is not appreciably reflected in strength properties, twisting of filaments can appreciably modify their

properties. This is particularly important for glass fibers. A less twisted filament is more completely impregnated with binder, increasing the strength and chemical resistance of reinforced plastics.

During the making of fibers, they are treated with a sizing agent, which must be removed in thermomechanical treatment [23, 34, 69] in order to boost the adhesion of resins and to enhance moisture and chemical resistance.

Synthetic binders. Various synthetic resins are used as binders for reinforced plastics. The type of binder selected characterizes the strength, physical, and processing properties of reinforced plastics and their cost.

Very heavily dependent on the binder chosen are the physical properties of materials, heat resistance, moisture resistance, chemical resistance, dielectric indicators, and the like. To a lesser extent, the type of binder influences the short-term static strength, while the long-term strength of reinforced plastics depends strongly on the type of binder [22].

According to the specific features of the construction and operation of chemical equipment, of greatest interest are binders based on unsaturated polyesters, epoxy, phenolic, furan, organosilicon, and certain other resins. The technology of the production and the properties of these resins have been examined closely in the literature [21, 23, 34, 35, 52, 58, 59, 62].

Let us confine ourselves to background information on the strength properties given in Table 3 [62] and to a brief characterization of resins.

Binders based on unsaturated polyester resins. The distinguishing feature of unsaturated polyester resins is their ability to cure at low temperatures and pressures. These resins are classed with the so-called contact type -- they do not contain a solvent in their constitution, and during their curing the liquid phase passes entirely into the solid phase without giving off volatile compounds. These properties are especially valuable in building large-size equipment. Of the domestically produced resins, resins of the following kinds are used: PN-1, PN-2, PN-3, PN-4, MGF-9, TMGF-11, and TGM-3.

Polyester resins of new kinds have been formulated: PN-6 and PN-10 stiff resins, PN-69 semistiff resins, and SKPS-1 and SKPS-2 elastic resins with relative elongation to 200 percent. Tables 4 and 5 [44] present the main properties of polyester resins.

Cobalt naphthenates and cobalt octenates are used as accelerators. To obtain glass-reinforced plastics with optimal properties, the amount of the oxide is recommended to be reduced to a minimum and the curing reaction rate should be regulated by the amount of accelerator added or by temperature. Table 6 [44] gives recommended compositions in parts by weight for the cold curing of polyester resins.

TABLE 3. PHYSICOMECHANICAL INDICATORS OF THE MAIN KINDS OF BINDERS

Показатели	2 Значения показателей для смол				
	3 поли-эфирных	4 эпоксид-ных	5 феноль-ных	6 меламе-новых	7 кремний-органиче-ских
8 Предел прочности в $\text{kg}/\text{mm}^2$ при:					
9 растяжении	4,2—7,0	2,8—9,1	4,2—6,3	4,9—6,3	2,8—3,5
10 изгибе	6,0—13,0	9,1—14,2	7,7—11,9	7,7—11,9	6,3—9,8
11 сжатии	9,1—25,5	10,5— 15,0	8,4—10,5	28,0— 31,5	6,3—10,5
12 Удельная ударная вязкость в $\text{kg}\cdot\text{м}/\text{cm}^2$	0,2—0,4	0,2—0,1	0,25— 0,40	0,24— 0,40	0,25—6,0
13 Модуль продольной упругости $E \cdot 10^{-2}$ в $\text{kg}/\text{cm}^2$	210—460	210—420	280—350	530—700	—
14 Относительное удлинение при разрыве $\epsilon$ в %	5	2—6	1,5—2,0	—	—
15 Коэффициент Пуассона	0,35— 0,42	0,4	0,35	—	—
16 Относительный температурный коэффициент линейного расширения $\alpha \cdot 10^6$ в $1/\text{град}$	7—10	3,1—9,0	2—6,5	—	—

KEY: 1 — Indicators

2 — Values of indicators for resins listed

3 — polyester

14 — Relative elongation at  
rupture,  $\epsilon$ , in %

4 — epoxy

15 — Poisson's ratio

5 — phenolic

16 — Relative temperature coef-  
ficient of linear expan-  
sion,  $\alpha \cdot 10^6$  deg $^{-1}$

6 — melamine

7 — organosilicon

8 — Ultimate strength in  
 $\text{kg}/\text{mm}^2$

9 — in tension

10 — in flexion

11 — in compression

12 — Specific impact toughness  
in  $\text{kg}\cdot\text{m}/\text{cm}^2$

13 — Modulus of lengthwise elasticity,  
 $E \cdot 10^{-2}$  in  $\text{kg}/\text{cm}^2$

TABLE 4. PHYSICOCHEMICAL INDICATORS OF UNSATURATED POLYESTER RESINS

Показатели	2 Значения показателей для полифенольных смол марок											
	3 ПН-1	4 ПН-1С	5 ПН-2	6 ПНМ-2	7 ПН-3	8 ПН-4	9 ПН-5	10 ПН-62	11 ПН-7	12 ПНМ-8	13 ПН-10	14 ПН-11
16 Содержание стирола в %	31—34	25—27	23—26	—	29—31	29—33	0	23—31	—	44—46	0	30—36
17 Кислотное число в $\text{мг} (\text{KOH})/\text{г}$	23—30	18—24	26—34	20—25	20—32	15—25	14—19	21—28	20—25	49—50	14—19	20—30
18 Плотность в $\text{г}/\text{см}^3$	1,13—1,16	1,18—1,25	1,18—1,23	1,17—1,18	1,14—1,17	1,14—1,16	1,31—1,32	1,25—1,27	1,25—1,26	1,12—1,14	1,07—1,08	1,16—1,18
19 Вязкость $\mu \cdot 10^{-4}$ в $\text{кг} \cdot \text{сек}/\text{м}^2$	4,9—7,84	19,6—27,2	36,1—58,7	3,92—6,87	4,9—9,8	5,87—12,7	10,8—17,65	8,83—15,72	11,75—14,7	4,9—8,83	9,8—12,7	9,8—14,7
20 Время гелеобразования при 20°C в присутствии 6 вес. ч. гипериза и 8 вес. ч. ускорителя НК на 100 вес. ч. смолы) в $\text{мин}$	60—120	60—180	60—120	80—120	60—130	60—180	120—300	—	60—90	250—350*	180—300	—

\* Gel formation time in the presence of 2 parts by weight of a 50 percent paste of cyclohexanone peroxide and NR  $\text{natural rubber}$  accelerator

\*\* Gel formation time in the presence of 1 part by weight of a 50 percent paste of benzene peroxide and 1 part by weight of dimethyl aniline solution

KEY: 1 — Indicators

2 — Values of indicators for polyester resins of grades listed

3 — PN-1      13 — PN-10

4 — PN-1S     14 — PN-11

5 — PN-2     15 — PN-69

6 — PNM-2    16 — Styrene content in %

7 — PN-3      17 — Acid number in  $\text{mg} (\text{KOH})/\text{g}$

8 — PN-4      18 — Density in  $\text{g}/\text{cm}^3$

9 — PN-6      19 — Viscosity,  $\mu \cdot 10^{-4}$   $\text{kg} \cdot \text{sec}/\text{m}^2$

10 — PN-62    20 — Gel formation time (at 20°C in the presence of 6 parts by

the presence of 6 parts by

20 /continued/ weight glycerin  
and 8 parts by weight NR  
accelerator per 100 parts  
by weight resin) in minutes

TABLE 5. PHYSICOMECHANICAL INDICATORS OF CURED POLYESTER RESINS

Показатели	Значения показателей для полиэфирных смол марок											
	ПН-1СУ 3	ПН-1С 4	ПН-2 5	ПН-2 6	ПН-3 7	ПН-4 8	ПН-6 9	ПН-7 10	ПН-8 11	ПН-10 12	ПН-11 13	ПН-69 14
16 Плотность в $\text{g}/\text{cm}^3$	1,21— 1,28	1,33— 1,34	1,26— 1,29	1,26— 1,27	1,22— 1,25	1,21— 1,25	1,40— 1,42	1,32— 1,35	1,22— 1,23	1,18— 1,21	1,28— 1,29	1,18— 1,21
17 Твердость по Бринелю	14—18	15—22	17—24	12—14	10—15	10—15	17—21	15—25	15—25	23—27	20—23	12—16
18 Пределы прочности в $\text{kN}/\text{cm}^2$ при:												
19 изгибе	825—1100	440—550	700—1050	550—650	600—850	500—800	300—420	500—700	560—870	650—750	240—300	500—600
20 растяжении	400—450	—	—	—	450—550	400—500	—	—	—	—	—	—
21 сжатии	800—1000	980—1085	1050— 1350	1150— 1350	800—1250	1000— 1200	1050— 1150	800—1250	500—700	1000— 1100	—	60—120
22 Модуль упругости изг. яз $E \cdot 10^{-4}$ в $\text{kN}/\text{cm}^2$	2,2—2,8	2,8—2,9	2,5—3,5	2,6—2,8	2,0—2,5	2,4—3,2	3,3—3,9	3,0—3,2	3,3—3,7	—	3,2—3,4	—
23 Удельная ударная вязкость в $\text{kJ}/\text{cm}^2$	6—10	3—4	2—5	—	7—11	4—8	2—3	3—5	3—5	2—3	5—6	55—100
24 Теплостойкость по Вика в °C	80—110	80—100	100—120	60—85	170—190	90—115	170—190	190—210	95—85	145—155	170—190	—
25 Водонаполнение за 24 ч в %	0,07— 0,15	0,05— 0,12	0,05— 0,10	0,08— 0,12	0,10— 0,22	0,10— 0,33	0,04— 0,09	0,10— 0,11	0,18— 0,22	0,07— 0,08	0,02— 0,04	0,12— 0,16
												0,47— 0,64

KEY: 1 — Indicators

2 — Values of indicators for polyester resins of grades listed

3 — PN-1СU 14 — PN-11  
4 — PN-1S 15 — PN-69  
5 — PN-2 16 — Density in  $\text{g}/\text{cm}^3$   
6 — PM-2 17 — Brinell hardness  
7 — PN-3 18 — Ultimate strength<sub>2</sub> values in  $\text{kg}/\text{cm}^2$   
8 — PN-4 19 — in flexion  
9 — PN-6 10 — in tension  
10 — PN-62 11 — in compression  
11 — PN-7 12 — Modulus of elasticity  
12 — PM-8 13 — PN-10  
13 — PN-10 in flexion,  $E \cdot 10^{-4}$  in  $\text{kg}/\text{cm}^2$ 

23 — Specific impact toughness

24 — Vicat heat resistance in °C

25 — Water absorption in 24 hours, in %

The initiator and the accelerator are added immediately before fabricating articles based on polyester resins, since resins containing curing additives retain fluidity and therefore can be molded in a limited time interval, defined as the gel formation time. The gel formation time depends on temperature, resin composition, initiating system, and the amount of initiating (curing) additives; it varies at 20° C from several minutes to several hours. Total curing at room temperature is achieved over a period of 10-15 days. Sometimes the articles are heat-treated at 100-130° C for several hours to speed up the process. The amount of initiating additives with recommended compositions can be varied within certain limits (cf. Table 6).

TABLE 6. RECOMMENDED COMPOSITIONS FOR COLD-CURING RESINS

A Компоненты	B Содержание компонентов в вес. ч. для составов			
	1	2	3	4
C Полиэфирная смола	100	100	100	100
D Гидрориз	3-6	-	-	-
E 50%-ный раствор перекиси метил-этоксикетона в диметилфталате	-	1-2	-	-
F 50%-ная паста перекиси циклогексанона в дибутилфталате	-	-	1-2	-
G 50%-ная паста перекиси бензоила в дибутилфталате	-	-	-	0,5-2
H Ускоритель НК	6-8	1-3	1-3	
I 10%-ный раствор диметиланилина в стироле	-	-	-	1-2

Remark. Compositions 1-3 are best used in processing the polyester resins PN-1, PN-2, PN-5, PN-4, PN-1S, PN-3S, PNM-2, and PNM-8, and composition 4 -- in processing resins PN-6, PN-7, and PN-69.

KEY: A -- Components                    G -- 50% paste of benzoyl peroxide  
 B -- Content of components            in dibutylphthalate  
       in parts by weight              H -- NR accelerator  
       for listed compositions  
 C -- Polyester resin                  I -- 10% solution of dimethyl  
 D -- Cumene hydroperoxide            aniline in styrene  
 E -- 50% solution of methyl ethyl ketone peroxide in  
       dibutyl phthalate  
 F -- 50% paste of cyclohexanone peroxide in dibutyl  
       phthalate

Besides the initiator and accelerator, other additives can be introduced into the binder composition, for example, fillers (chalk, talc, quartz flour, and diabase) and colorants.

The chemical resistance of polyester resins is determined by their composition. All kinds of polyester resins are resistant to aliphatic hydrocarbons. These resins are used in equipment that is in contact with petroleum products.

Polyester resins are resistant to mineral acids (with the exception of oxidizing acids -- nitric, chromic, and sulfuric -- at concentrations upwards of 70 percent), fresh and sea water, and certain organic solvents.

Since esters are hydrolyzed on treatment with strong alkalies, polyesters are unstable in these media. Weak alkalis and highly dilute solutions of caustic alkalis do not affect polyester resins. It must be borne in mind that the chemical resistance of polyester resins does not lend itself to a general determination, since their composition can change (can be modified), and thus chemical stability can be significantly modified.

A disadvantage of polyester resins is their flammability. When halogen-containing (mainly chlorine-containing) polyesters and antimony trioxide are added to a composition, flammability is reduced and flame resistance is enhanced [34].

Improvement in the properties of unsaturated polyesters is achieved by modifying them with various compounds.

Binders based on epoxy resins. Epoxy resins are linear polymers prepared by the polycondensation of epichlorhydrin or glycerin dichlorhydrin with hydroxyl-containing compounds. Epoxy resins in the uncured state contain, in their linear chains, free terminal epoxy (oxyethylene) groups, whose number determines the molecular weight, viscosity, and other properties of resins.

The wide use of epoxy resins in the production of glass-reinforced plastics is due to their high wettability and adhesion to glass fiber, low shrinkage during curing, high cohesive strength, and good compatibility with other resins. This permits improvements in the physicomechanical, anticorrosion, and other properties of glass-reinforced plastics by means of modification.

Anhydrides of dicarboxylic acids, for example, maleic and phthalic anhydrides, are the best curing agents to impart high heat resistance and low flammability to epoxy resins.

Disadvantages of epoxy resins include the following: high cost and toxicity, caused mainly by the toxicity of the curing agents used.

The heat resistance of epoxy resins is enhanced by combining and modifying them with other organic compounds. The cost of epoxy resins is lowered somewhat by combining them with inexpensive resins, for example, with polyester resin, and also by adding mineral fillers to their base as binders. The toxicity of epoxy resins can be eliminated by modifying them with compatible polymers.

Chemical resistance of epoxy resins. Usually it is assumed that epoxy resins are resistant to weak caustic alkalis, liquid fuel (gasoline and kerosene), oils, solvents, and acids, except for oxidizing acids, and most salt solutions.

Table 7 presents systems of curing agents for epoxy resin (viscosity of 0.09 kg·sec/m<sup>2</sup> and epoxy number of -0.54 eq/100 g). For all systems, the accelerator used was 2,4,6-tri(dimethylaminomethylene)phenol. Specimens 91.6x25.4x3.2 mm in size were kept at 25° C for 6 months in the following media: sodium chloride, sodium bisulfate, sodium carbonate, sodium hydroxide; ammonia solutions, sulfuric, hydrochloric, nitric, and glacial acetic acids, and organic solvents. In addition, the specimens were tested in water at room temperature and at the boiling point.

After being kept in 10 and 25 percent sodium chloride solutions and in a 10 percent sodium bisulfate solution, the resin cured with diaminodiphenylsulfone showed the greatest strength. Resin 956 showed the lowest chemical resistance in the media.

The resin cured with diaminodiphenylsulfone and with anhydrides revealed the best resistance in 3, 10, and 30 percent sulfuric acid solutions. The resin cured with the methyl anhydride "nedic" exhibited good results in 10 percent nitric acid.

Diaminodiphenylsulfone and borotrifluoromonoethylamine provide the best chemical resistance in 10 and 25 percent sodium hydroxide solutions, 25 percent sodium carbonate solutions, and 25 percent ammonia solution.

All curing agents give good results in gasoline, benzene, ethyl alcohol, and ethylene glycol.

Resins cured with anhydrides and diaminodiphenylsulfone are stable in water at room temperature, but only resins cured with diaminodiphenylsulfone are stable in boiling water.

Experiments showed that the diaminodiphenylsulfone curing agent provides the best chemical stability for resins (the greatest "universality").

Good alkaline-resistance of epoxy resins is achieved by using the curing agents meta-phenylenediamine and triethylenetetramine.

Hexamethylenediamine and polyethylenepolyamine impart resistance to epoxy resins in caustic alkalis and sulfuric acid.

TABLE 7. SYSTEMS OF CURING AGENTS FOR EPOXY RESIN

<sup>1</sup> Количество отвердителя по 100 вес. ч. смолы	<sup>2</sup> Режим отверждения	<sup>3</sup> Предел прочности при изгибе в кг/см <sup>2</sup>
<sup>4</sup> 65 вес. ч. фталевого ангидрида	<sup>5</sup> 24 ч при 140° С	1388
<sup>6</sup> 80 вес. ч. метилового ангидрида и 2 вес. ч. 2, 4, 6- три-(диметиламино- метилен)- фенола	<sup>7</sup> 12 ч при 180° С и 12 ч при 250° С	1410
<sup>8</sup> 35 вес. ч. диаминодифенилсуль- фона	<sup>9</sup> 6 ч при 135° С и 12 ч при 180° С	970
<sup>10</sup> 25 вес. ч. отвердителя 956	<sup>11</sup> 24 ч при 25° С и 24 ч при 40° С	1096
<sup>12</sup> 4 вес. ч. бортрифторомоэтиламина	<sup>13</sup> 6 ч при 80° С, 6 ч при 120° С и 12 ч при 150° С	1040

KEY: 1 -- Amount of curing agent per 100 parts by weight resin

2 -- Curing regime

3 -- Ultimate strength in flexion, in kg/cm<sup>2</sup>

4 -- 65 parts by weight phthalic anhydride

5 -- 24 hours at 140° C

6 -- 80 parts by weight methyl anhydride and  
2 parts by weight of 2,4,6-tri(dimethyl-  
aminomethylene)phenol

7 -- 12 hours at 180° C and 12 hours at 250° C

8 -- 35 parts by weight diaminodiphenylsulfone

9 -- 6 hours at 135° C and 12 hours at 180° C

10 -- 25 parts by weight, curing agent 956

11 -- 24 hours at 25° C and 24 hours at 40° C

12 -- 4 parts by weight borotrifluoromonoethylamine

13 -- 6 hours at 80° C, 6 hours at 120° C, and  
12 hours at 150° C

Thus, the choice of curing agent and the curing regime of the resin and of the reinforced plastics based on it strongly affect the chemical resistance of epoxy resins.

Binders based on furan (furyl) resins. Furan resins are characterized by a good and inexpensive starting material base, and also by high chemical resistance.

Furan resins can be cured at room and at elevated temperatures. Acids of the type of phosphoric or paratoluolsulfoxy acids and sulfoxychlorides are used as curing agents. Furan resins are marked by good workability, fluidity, and wetting ability. The shelf life of furan resins is 2 or more years even in tropical climate conditions, while polyester resins retain their workability only for 6 months.

It must be noted that furan resins are inferior in adhesive qualities to epoxy and polyester resins; as a result, the mechanical properties of furan glass-reinforced plastics are below glass-reinforced plastics based on epoxy and polyester resins.

Domestic grades of modified furan resins prepared by blending with polyvinylacetals, and with epoxy and other resins have been developed.

The chemical resistance of furan resins has not yet been studied adequately.

Cured furan resins are exceptionally resistant to organic solvents (dichloroethane, ethyl alcohol, and so on), nonoxidizing mineral and organic acids, salts, and alkalis. In chemical resistance, furan resins approach phenol-formaldehyde resins. Furan resins have low water absorption; they are heat resistant and resistant to abrasion.

Binders based on phenol-formaldehyde resins. Phenol-formaldehyde resins began to be used, earlier than many other resins, in the production of reinforced plastics: faolite, textolite, textofaolite, glass-reinforced textolites, and so on. Their wide use is due to their high chemical and heat resistance.

Use of certain types of phenolic resins in the fabrication of large-size articles using plastics based on these resins is somewhat limited owing to their content of solvents and water, which requires that they be cured at increased pressure ( $70-500 \text{ kg/cm}^2$ ) and elevated temperatures ( $130-140^\circ \text{ C}$ ).

Phenol-formaldehyde resins are resistant to mineral acids (except for oxidizing acids): hydrochloric acid -- at any concentration; sulfuric acid -- up to 70 percent; glacial acetic and unconcentrated phosphoric and nitric acids -- up to 5 percent; salt solutions and the following solvents: acetone, ethyl alcohol, benzene, carbon tetrachloride, trichloroethylene, and so on. These resins are not resistant to alkalis.

To mold phenol-formaldehyde resins at reduced pressures (down to  $7 \text{ kg/cm}^2$ ) and thus to expand the possibilities of employing glass-reinforced plastics based on these resins, they are modified -- for example -- with polyvinylacetals, polyepoxides, alkyds, and so on.

Foreign literature contains reports on the development of glass-reinforced plastics based on phenolic resins cured at low pressures (1.0-3.5 kg/cm<sup>2</sup>) [62]. One of the most important characteristics of phenolic resins intended for curing at low pressure is high heat resistance and thermostability. They can withstand temperatures to 200° C for long periods of time.

Several grades of glass-reinforced plastics based on modified phenol-formaldehyde resins are produced in the USSR: the glass-reinforced textolites KAST, KAST-V, VPT, VFT-S, and FN, glass-reinforced veneer based on EF-2 resin, the glass-reinforced voloknit [fiber-filled molding compound] grades AG-4S, AG-4V, and DSV, faolites, textolites, and so on.

Binders based on organosilicon resins. High heat resistance (to 400° C) and resistance to various corrosive reagents (mineral acids, alkalis, salt solutions, and solvents) account for the use of organosilicon resins, mainly polymethyl siloxane and polymethylphenyl siloxane resins, in the production of glass-reinforced plastics.

Through the use of polyvinyl siloxane resins, it is possible to make glass-reinforced textolites at low pressures -- 2.0-2.5 kg/cm<sup>2</sup>.

Improvement in the properties of organosilicon resins is achieved by modifying them, for example, with epoxy and polyester resins.

The maximum elongation of the binder in tension is vitally significant in the deformation of reinforced plastics. By chemical modification, a moderate gain in resin elongation can be achieved without appreciable reduction in strength and in the modulus of elasticity.

#### Types of Reinforced Plastics

Faolite, textofaolite, and glass-reinforced faolite. These materials are classified as fibrous molding compounds.

At the present time, two grades of faolite -- faolite A and faolite T -- are widely used in the chemical industry. These faolites are made on the basis of resol-type phenol-formaldehyde resins.

To make grade A faolite used in pipe fabrication, 152 parts by weight anthophyllite asbestos and 8 parts by weight chrysotile asbestos are combined per 100 parts by weight resol resin; in sheet fabrication, 95 parts by weight anthophyllite and 5 parts by weight chrysotile asbestos are used per 100 parts by weight resin.

In making grade T faolite intended for pipe fabrication, 16 parts by weight chrysotile asbestos and 100 parts by weight ground graphite are combined with 100 parts by weight resin; in making sheets, 20 parts by weight chrysotile asbestos and 80 parts by weight ground graphite are used

TABLE 8. PHYSICOMECHANICAL PROPERTIES OF FAOLITE

Марка фолита	Плотность в г/см <sup>3</sup>	Коэффициент теплопро- водности в ккал/(м· <sup>2</sup> · <sup>0</sup> · <sup>0</sup> )	Удельная вязкость в кг·с/см <sup>2</sup>	Темпера- туросто- йкость по Мартенсу в °C	Кислото- стойкость в %	7 Предел прочности в кг/см <sup>2</sup> при				
						8 изгиб	9 скатие	растяже- ние 10	11 срезе	
A	1,5	0,25	3,44	135	0,8	590—600 260—280	590—900 580—900	120—200 310—385	300—380 240—350	
T	1,65	0,90	3,28	126	0,6	590—600 260—280	590—900 580—900	120—200 310—385	300—380 240—350	

Remarks: 1. Brinell hardness is 20 kg/mm<sup>2</sup> for all faolite grades; the relative temperature coefficient of linear expansion  $\alpha$  is  $2.0\text{--}3.0 \cdot 10^{-5}$  deg<sup>-1</sup>.

2. Acid resistance is the change in weight of a standard bar in 22 percent HCl for 24 hours at the temperature of a boiling-water bath.

3. The ultimate strength is given in the crosswise direction in the fiber -- in the numerator, and in the lengthwise fiber direction -- in the denominator.

KEY: 1 -- Faolite grade  
 2 -- Density in g/cm<sup>3</sup>  
 3 -- Coefficient of thermal conductivity in kcal/(m·hr.deg)  
 4 -- Specific impact toughness in kg·cm/cm<sup>2</sup>  
 5 -- Martens heat resistance in °C  
 6 -- Acid resistance in percent  
 7 -- Ultimate strength in kg/cm<sup>2</sup>  
 8 -- in flexion  
 9 -- in compression  
 10 -- in tension  
 11 -- in shear

per 100 parts by weight resin. The physicomechanical properties of faolite are given in Table 8. Owing to its relatively high thermal conductivity, grade T faolite is used in making heat exchangers. Additionally, in contrast to grade A faolite, grade T faolite is resistant to hydrochloric acid. Table 9 presents data on the chemical resistance of faolite.

Finished structures (piping, fittings, cylindrical shells, and so on) and also semifinished products in the form of facelite sheets of different thicknesses and dimensions are made of facelite. Faolite sheets in the uncured state are sent to fabricating plants, where various fittings, cylindrical vessels, shells, cylindrical shells, equipment, and so on are made from the faolite sheets by molding on wooden and metal molds. Facelite sheets can be used as insert liner material.

When fabricating articles from faolite, it must be considered that the material shrinks by 2-3 percent during curing. Molds containing faolite are initially subjected to incomplete heat treatment in a chamber for 12-14 hours at 90° C (the heating is stepwise). Then the mold is taken from the chamber flaws are eliminated, and the article is machined (facing), and then the entire article is coated with bakelite varnish. Thereupon, a final heat treatment is conducted to cure the faolite, for a period of 10 hours at 130° C.

Individual cylindrical shells and parts made of faolite can be connected by cemented unions using faolite cement. Cemented surfaces are finished at an angle of 45° or else a lengthwise groove 8 mm in diameter is made along the butt edges, into which the faolite compound is introduced. The cemented seam is treated according to the temperature regime of faolite curing. Parts of grade A faolite can be joined with cement consisting of 100 parts by weight of resol resin and 50 parts by weight anthophyllite asbestos, and parts made of grade T faolite -- with a cement consisting of 100 parts by weight resol resin, 40 parts by weight chrysotile asbestos, and 40 parts by weight ground graphite.

For improved physicomechanical indicators of faolite, it can be reinforced with several layers of cotton, silk, or glass cloth. In this case, the material is called textofaolite or glass-reinforced faolite, depending on the kind of reinforcing cloth used.

Textofaolite and glass-reinforced faolite, exhibiting low relative temperature coefficients of linear expansion and high mechanical strength, can be used in making large-size articles subjected to appreciable mechanical loads. For example, a still 1400 mm in diameter and 2700 mm in height was made of textofaolite. This still operated in a hexachlorane environment.

Textolites. Textolites are complex materials made by pressing stacks of cotton and silk cloth impregnated with phenol-formaldehyde resin and cured at 145-150° C at a pressure of 100-110 kg/cm<sup>2</sup>.

Generally, textolite piping is used in the chemical industry. Piping is made by winding cloth impregnated with resin on a metal mandrel heated to 60° C.

TABLE 9. MECHANICAL PROPERTIES OF PAOLITE AFTER EXPOSURE  
TO CORROSION MEDIA AT ROOM TEMPERATURE (INITIAL ULTIMATE  
STRENGTH  $462 \text{ kg/cm}^2$  AND INITIAL IMPACT TOUGHNESS  $5.1 \text{ kg}\cdot\text{cm}/\text{cm}^2$ )

A Среда	Б Концентрация %	C Удельная ударная вязкость в $\text{kG}\cdot\text{см}/\text{см}^2$ после выдержки в среде в течение				D Предел прочности при статическом изгибе в $\text{kG}/\text{см}^2$ после выдержки в течение	
		E 1 мес.	F 3 мес.	G 12 мес.	H 80 мес.	I 6 мес.	J 12 мес.
K Соляная кислота	10	4,8	4,3	4,5	4,2	314	377
	22	—	—	—	—	418	303
	30	4,6	5,2	4,9	—	—	—
L Серная кислота	10	4,5	4,2	4,7	4,5	430	374
	30	—	—	—	—	480	439
	98	—	—	—	—	216	Образцы полуразрушены
M Уксусная кислота	20	—	—	—	—	450	379
	50	4,5	4,7	4,3	—	—	—
	92	—	—	—	—	501	429
N Уксусный ангидрид	94	—	—	—	—	328	361
P Этиловый спирт	—	3,8	4,7	5,3	3,4	—	—
Q Метиловый спирт	—	4,8	4,3	5,7	3,5	—	—
R Вода	—	3,7	3,7	4,2	4,1	—	—
S Этилацетат 84% + уксусная кислота 8%	--	—	—	—	—	463	324
T Метиленхлорид (плотность $1,33 \text{ г}/\text{см}^3$ )	—	—	—	—	—	419	393

KEY (on the following page)

KEY /to TABLE 9 on preceding page/:

- A -- Medium
- B -- Concentration in %
- C -- Specific impact toughness in kg·cm/cm<sup>2</sup>
- D -- Ultimate strength in static flexion in kg/cm<sup>2</sup>  
after exposure for time listed
- E -- 1 month
- F -- 3 months
- G -- 12 months
- H -- 80 months
- I -- 6 months
- J -- 12 months
- K -- hydrochloric acid
- L -- Sulfuric acid
- M -- Acetic acid
- N -- Acetic anhydride
- O -- Specimens are semifailed
- P -- Ethyl alcohol
- Q -- Methyl alcohol
- R -- Water
- S -- 84% ethyl acetate and 8% acetic acid
- T -- Methylene chloride (density of 1.33 g/cm<sup>3</sup>)

The practice of protecting parts (of mixers, condensers, and so on) by winding them with textolite fabric, followed by treatment at 130° C. Also made from textolite are pump parts, protective sleeving of shafts, and internal parts of fractionation columns.

Asbovinyl and texto-asbovinyl. Asbovinyl is a polymerization plastics compound prepared by blending finely ground with the varnish ethynol (di-vinylacetylene varnish). The following amounts of starting materials in parts by weight are used in making crude asbovinyl compound:

Ethynol varnish (recalculated on a 45 percent basis)	65.5
Anthophyllite asbestos .....	28.5
Chrysotile asbestos .....	6.0

In many of its properties, asbovinyl is similar to faolite, however its adhesion is much higher.

Asbovinyl is used as an independent structural material and as a lining material. Asbovinyl compound is cured at high temperatures (120-130° C) by a stepwise regime.

TABLE 10. PHYSICOMECHANICAL PROPERTIES OF ASBOVINYL.

/ Показатели	2 Значения показателей для асбовинилов, состоящих из		
	3 аэтофидлантового асбеста и немодифицированного лака этиналь	4 модифицированного графита (30%) и битума (43,6%)	5 смеси аэтофидлантового (80%) и хризотилового асбеста (20%), лака этиналь, модифицированного битумом
6 Предел прочности в кГ/см <sup>2</sup> при: 7 сжатии 8 растяжении 9 статическом изгибе	200—350 150—215 130—300	— — 130—150	260 — 130—160
10 Удельная ударная вязкость в кГ× х см/см <sup>2</sup>	2,9	2,9	2,9
11 Твердость по Бринелю	18—25	13	15
12 Адгезия к стали в кГ/см <sup>2</sup> на: 13 отрыв 14 сдвиг	22 25	26 28	19 25
15 Теплостойкость в °C	150	90	100
16 Термостойкость (число теплосмен при 150° C)	10	10	10
17 Относительный температурный коэффициент линейного расширения $\alpha \cdot 10^6$ в 1/град	2,4	2	2,75
18 Удельная теплоемкость в ккал/(кг× х град)	0,154	0,150	—
19 Коэффициент теплопроводности в ккал/(м·ч·град)	0,11	0,13	—
20 Водопоглощаемость в % для: 21 лакированного асбовинила 22 нелакированного асбовинила	0,13 1,1	0,41 1,04	0,16 1,0
23 Плотность в г/см <sup>3</sup>	1,4—1,5	1,5	—

KEY to TABLE 10 is given on the following page

KEY [to TABLE 10 on preceding page]:

- 1 -- Indicators
- 2 -- Values of indicators for asbovinyls consisting of
- 3 -- anthophyllite asbestos and unmodified ethynol varnish
- 4 -- modified graphite (50%) and asphalt (43.5%)
- 5 -- a mixture of anthophyllite (80%) and chrysotile asbestos (20%), ethynol varnish, and modified asphalt
- 6 -- Ultimate strength in kg/cm<sup>2</sup>
- 7 -- in compression
- 8 -- in tension
- 9 -- in static flexion
- 10 -- Specific impact toughness in kg·cm/cm<sup>2</sup>
- 11 -- Brinell hardness
- 12 -- Adhesion to steel in kg/cm<sup>2</sup>
- 13 -- in parting
- 14 -- in shear
- 15 -- Heat resistance in °C
- 16 -- Thermostability (number of heat changes at 150° C)
- 17 -- Relative temperature coefficient of linear expansion,  
 $\alpha \cdot 10^5$  deg<sup>-1</sup>
- 18 -- Specific heat capacity in kcal/(kg·deg)
- 19 -- Coefficient of thermal conductivity in kcal/(m·hr·deg)
- 20 -- Water absorption in % for
- 21 -- varnished asbovinyl
- 22 -- unvarnished asbovinyl
- 23 -- Density in g/cm<sup>3</sup>

Tables 10 and 11 present the main physicomechanical and anticorrosion properties of asbovinyl.

By reinforcing asbovinyl with cotton cloth, one can obtain textured asbovinyl, exhibiting greater mechanical strength.

Glass-reinforced plastics. A broad array of reinforced plastics produced on the basis of synthetic resins and glass fibers is grouped under the term "glass-reinforced plastics." Depending on glass fiber orientation, glass-reinforced plastics can be divided into two groups: with oriented and with randomly arranged reinforcements.

Physicomechanical and other characteristics depend on the type of glass-reinforced plastics. Tables 12, 13, and 14 [1, 47] present properties of glass-reinforced plastics and their resistance in chemical media and in water.

TABLE 11. CHEMICAL RESISTANCE OF ASBOVINYL IN VARIOUS CORROSIVE MEDIA

Среда	Концентрация в %	Температура в °C	Химическая стойкость асбовинила с различным наполнителем						
			Anthophyllite 5)	Хриотноло- вый	Anthophyllite тотина (80%) и хриотноло- вой (20%)	Anthophyllite тотина (80%) и графитомын (20%)	Anthophyllite тотина (80%) и графитомын (20%)	Anthophyllite тотина с до- бавкой би- туна	Хриотноло- вый (80%) и графито- мый (20%)
II Азотная кислота	10	20	У	У	—	—	—	—	—
12 Едкий натр	10	20	У	У	У	У	У	У	У
	20	20	У	У	УУ	У	У	У	У
	50	20	Н	У	Н	—	Н	—	
	20	100	У	Н	У	У	У	Н	
13 Серная кислота	До 30	80	УУ	Н	—	—	—	—	—
	40	100	У	Н	У	У	У	Н	
	60	100	Н	Н	Н	У	У	Н	
	65	20	У	Н	—	—	—	—	
	80	100	Н	Н	Н	Н	Н	Н	
	20	20	У	—	—	—	—	—	
14 Соляная кислота	20	40	УУ	—	—	—	—	—	
	20	100	У	У	—	—	—	—	
	30	100	Н	Н	У	У	У	Н	

Remark. У = resistant; УУ = somewhat resistant  
Н = nonresistant

KEY: 1 — Medium

2 -- Concentration in %

3 -- Temperature in °C

4 -- Chemical resistance of  
asbovinyl with various  
fillers

5 -- Anthophyllite

[KEY continued on following page]

KEY /to TABLE 11 on the preceding page<sup>7</sup>:

- 6 -- Chrysotile
- 7 -- Anthophyllite (80%) and chrysotile (20%)
- 8 -- Anthophyllite (50%) and graphite (50%)
- 9 -- Anthophyllite with asphalt additive
- 10 -- Chrysotile (80%) and graphite (20%)
- 11 -- Nitric acid
- 12 -- Sodium hydroxide
- 13 -- Sulfuric acid
- 14 -- Hydrochloric acid

Of greatest in chemical equipment making are cold-curing glass-reinforced plastics not requiring high specific pressures when used in molding articles.

Laminated plastics based on synthetic fibers. Reinforced structural plastics in which synthetic fibers (acetate, acryl, capron, fluorlons, and so on) are used as the reinforcements can be made according to the textolite and glass-reinforced plastics types.

In principle, the production of these plastics has several features determined mainly by the properties of the fibers and the adhesion thereto of the synthetic resins.

Reinforced thermoplastics and combination laminated plastics. Glass fibers are used to reinforce the following thermoplastics with the aid of several industrial procedures: polyethylene, polypropylene, fluoroplastics, polyvinylchloride, and so on.

This material exhibits the high strength typical of reinforced plastics and the high chemical resistance typical of thermoplastics. At the present time, industry has begun to master the production of thermoplastics doubled with glass cloth. This will lead to the strengthening of thermoplastics with glass-reinforced plastics in the future in equipment making.

In the designing and building of chemical equipment, depending on its service conditions and the requirements placed on the items, various reinforced plastics can be combined, for example, one can combine faolite with glass-reinforced plastics, combine various types of glass-reinforced plastics, and so on.

TABLE 12. PHYSICOMECHANICAL INDICATORS OF GLASS-REINFORCED TEXTOLITE  
BASED ON UNSATURATED POLYESTER RESINS (TYPE T<sub>1</sub>, GLASS CLOTH)

Показатели	2 Значения физико-механических показателей для полимерных смол следующих марок						
	3 ПН-1	4 ПНМ-2	5 ПН-3	6 ПН-4	7 ПН-6	8 ПН-62*	9 ПН-10*
11 Предел прочности в кГ/см <sup>2</sup> при:							
12 растяжении	2800—3200	—	2500—3000	2900—3450	—	2950—3850	—
13 изгибе	2000—2500	2500—2800	1900—2400	2000—2400	1900—2250—4000	3450—3650	2500—2600
14 скатии (параллельно слоем)	900—1100	1000—1300	970—1100	1000—1200	960—1260	1800—2600	1200—1400
15 Модуль упругости при изгибе E · 10 <sup>-4</sup> в кГ/см <sup>2</sup>	11,6—12,3	15,5—16,5	11,0—13,0	12,0—14,0	16,2—17,5	13,0—16,5	15,0—16,0
16 Удельная ударная вязкость в кГ·см/см <sup>3</sup>	255—320	235—260	240—290	235—315	280—460	240—330	240—270
17 Теплостойкость по Мартенсу в °C	88—100	—	180—185	196—205	80—95	260—280	240—250
18 Водопоглощение за 24 ч в %	0,50—0,52	0,12—0,16	0,45—0,51	0,33—0,50	0,10—0,16	0,08—0,12	0,04—0,06

\* ASIT Glass Cloth (b) — S<sub>2</sub>-0

KEY: 1 — Indicators  
2 — Values of physicomechanical indicators  
for polyester resins of the following  
grades

- |           |            |  |
|-----------|------------|--|
| 3 — PN-1  | 7 — PN-6   | 11 — Ultimate strength in kg/cm <sup>2</sup> |
| 4 — PNM-2 | 8 — PN-62* | 12 — in tension                              |
| 5 — PN-3  | 9 — PN-10* | 13 — in flexion                              |
| 6 — PN-4  | 10 — PN-11 | 14 — in compression (parallel to layers)     |
- KEY continued on following page*

TABLE 13. ULTIMATE STRENGTH OF GLASS-REINFORCED TEXTOLITE BASED ON EPOXY RESIN AFTER EXPOSURE TO CORROSIVE MEDIA FOR 1 YEAR

Среда 3	Предел прочко- сти при натяже- нии в кг/см <sup>2</sup>	2		Предел прочно- сти при натяже- нии в кг/см <sup>2</sup>	2		Предел прочко- сти при натяже- нии в кг/см <sup>2</sup>
		Среда 1	Среда 2		Среда 1	Среда 2	
Воздух (исход- ная прочность)	5060	3% -ная серная кислота	11	3380	Сухой хлор	20	Разруше- ние 19
Дистиллиро- ванная вода	4990	70% -ная сер- ная кислота	12	2180	Этиленгликоль	21	4920
1% -ный щелкий натр	4230	10% -ная соля- ная кислота	13	3520	Ацетон	22	3070
20% -ный щелкий натр спирт	4980	37% -ная соля- ная кислота	14	2770	Метилэтаноле- тон	23	5120
10% -ный нашатыр- ный спирт	2360	30% -ная азот- ная кислота	15	350	Изопропиловый спирт	24	4620
25% -ный нашатыр- ный спирт	2060	10% -ная фос- форная кислота	16	4940	Бутиловый спирт	25	5250
10% -ная уксус- ная кислота	4250	95% -ная фос- форная кислота	17	4960	Этилапетат	26	4820
Линая уксус- ная кислота	4570	Цавелевая кислота	18	Разру- щение	Дихлорэтилен	27	4890

KEY to TABLE 13 is given on the following page

KEY /to TABLE 13 on preceding page/:

- 1 -- Medium
- 2 -- Ultimate strength in flexion in kg/cm<sup>2</sup>
- 3 -- Air (initial strength)
- 4 -- Distilled water
- 5 -- 1% sodium hydroxide
- 6 -- 20% sodium chloride
- 7 -- 10% ammonium hydroxide
- 8 -- 25% ammonium hydroxide
- 9 -- 10% acetic acid
- 10 -- Glacial acetic acid
- 11 -- 30% sulfuric acid
- 12 -- 70% sulfuric acid
- 13 -- 10% hydrochloric acid
- 14 -- 37% hydrochloric acid
- 15 -- 30% nitric acid
- 16 -- 10% phosphoric acid
- 17 -- 95% phosphoric acid
- 18 -- Oxalic acid
- 19 -- Failure
- 20 -- Dry chlorine
- 21 -- Ethylene glycol
- 22 -- Acetone
- 23 -- Methyl ethyl ketone
- 24 -- Isopropyl alcohol
- 25 -- Butyl alcohol
- 26 -- Ethyl acetate
- 27 -- Dichloroethylene
- 28 -- Trichloropropane
- 29 -- Epichlorhydrin
- 30 -- Allyl alcohol
- 31 -- Octane alcohol
- 32 -- Phenol
- 33 -- Brake fluid

TABLE 14. PHYSICOMECHANICAL PROPERTIES OF GLASS-REINFORCED PLASTICS CONTAINING VARIOUS REINFORCING MATERIALS

Основа стеклопластика <sup>1</sup>	Предел прочности при растяжении в кг/см <sup>2</sup> <sup>2</sup>		Предел прочности при изгибе в кг/см <sup>2</sup> <sup>3</sup>		Водопоглощение за время испытаний в % <sup>4</sup>
	до испытаний <sup>5</sup>	после выдержки в воде в течение 6 мес. <sup>6</sup>	до испытаний <sup>5</sup>	после выдержки в воде в течение 6 мес. <sup>6</sup>	
Жгутовая стеклоткань и полиэфирная смола	1880	1170	980	430	3,0
Гарнитурная стеклоткань и полиэфирная смола	2510	2080	1870	1270	2,3
Гарнитурная стеклоткань и фенолоформальдегидная смола	2440	2070	1900	1480	1,4
Стеклохолст и полиэфирная смола <sup>10</sup>	820	460	570	200	1,8

KEY: 1 -- Basis of glass-reinforced plastics  
 2 -- Ultimate strength in tension in kg/cm<sup>2</sup>  
 3 -- Ultimate strength in flexion in kg/cm<sup>2</sup>  
 4 -- Water absorption in test period in %  
 5 -- prior to tests  
 6 -- after exposure in water for 6 months  
 7 -- Roving glass cloth and polyester resin  
 8 -- Card-clothing glass cloth and polyester resin  
 9 -- Card-clothing glass cloth and phenol-formaldehyde resin  
 10 -- Glass lap and polyester resin

## CHAPTER TWO

### CHANGES IN THE PROPERTIES OF REINFORCED PLASTICS DURING THEIR LOADING

Polymer mechanics is at present in its formative stage. Devising methods for calculating structures made of reinforced plastics is complicated to a large extent by the anisotropy of the properties, which entails the use of cumbersome mathematical concepts.

Polymeric materials and plastics are marked by a high-elastic component of total deformation, which is not to be found in metals and alloys. Additionally, the strength properties of plastics depend heavily on the rate of deformation, temperature, and ambient environment.

These features of polymeric materials are due to their molecular structure. As a rule, when polymers are being deformed, the external loads will be counteracted by the forces of intermolecular bonds and only at the moment of actual rupture will the external force overcome chemical bonds along the cross-sectional area.

Strength indicators of plastics depend strongly on temperature and deteriorate rapidly with temperature increase. This temperature function becomes even more intensified when polymers are in contact with a corrosive environment.

#### Features of Deformation and Failure

Experimentally derived strain curve vary for different types of glass-reinforced plastics, which is determined by the composition, loading scheme, temperature regime, ambient environment, and other factors. It must be noted that the nature of the deformation of glass reinforcements and binder differs. In dealing with problems of the mechanics of glass fiber materials, usually one regards glass fiber as an ideally elastic body 14, 55.

But the binders can vary widely even when compared with each other. Some types of polyester and epoxy resins are closer to elastic bodies in their deformation properties than are plasticized resins (for example,

epoxy thiokol and polyester resins modified with synthetic rubber). For the main types of reinforced plastics, one can neglect the high-elastic component of deformation from the engineering standpoint.

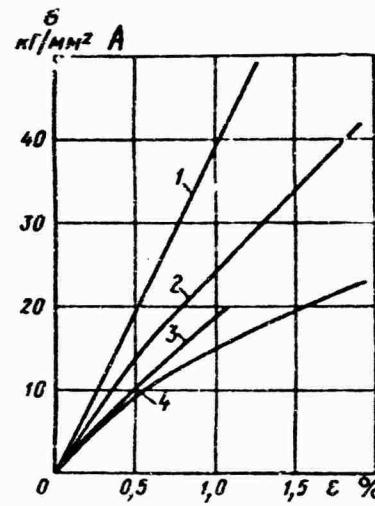


Fig. 2. Strain curves of glass-reinforced plastics of the following grades (at room temperature):

- 1 — 27-63S (unidirectional fiber lay-up)
- 2 — 27-63S (mutually perpendicular lay-up of fibers in the 1:1 ratio)
- 3 — AG-4S (mutually perpendicular lay-up of fibers in the 1:1 ratio)
- 4 — glass-reinforced textolite incorporating epoxy-phenolic binder)

KEY: A --  $\sigma$ , kg/mm<sup>2</sup>

In calculations, some glass-reinforced plastics can be considered as elastic bodies with an accuracy that suffices for practical purposes, at moderate loading ( $\sigma_w \leq 0.4 \sigma_f$ ) [ $w$  = working;  $f$  = fiber]. Fig. 2 presents typical strain curves of glass-reinforced plastics with different fiber lay-up arrangements when loaded all the way to rupture. Stiff (curves 1, 2, and 3) and plastic (curve 4) binders were used in these cases. Deformation was executed at the same rate. As we can see, only in curve 4 can we note a deviation from a straight line, though over the initial section the curve completely obeys Hooke's law. It was established that prior loading of glass-reinforced loading cannot affect the nature of the strain curve of unidirectional materials. Nor can temperature affect the course of these curves (Fig. 3).

It was also established that when glass-reinforced plastics are tested in corrosive solutions in the stressed and in the prestressed states, the linear nature of the strain-stress function remains unchanged (Fig. 4). It was also shown that variation in the rate of deformation all the way up to impact loading does not alter the qualitative pattern of the function  $\sigma = f(\epsilon)$ ; here only the short-term static strength and the modulus of elasticity change.

Only when oriented glass-reinforced plastics are deformed at an angle to the axes of elastic symmetry is the nonlinearity of the function  $\sigma = f(\epsilon)$  observed even at the initial stage owing to the manifestation of the inelastic properties of the binder.

It must be noted that underlying the methods of determining the elastic constants of materials and strength calculation is the hypothesis to the effect that reinforced plastics, in all stages of loading, behave as a continuous monolithic material and that the mechanism of the transmission of forces in the binder-reinforcing fiber system remains unchanged at all stages. In other words, reinforced plastics are considered as a homogeneous medium.

In cases when the polymer acts as an impregnating material (the reinforcing fibers are hydrophobic), for example, for textalites, the hypothesis of material homogeneity is quite to be expected. In the cases when the polymer exhibits the function of only a binder, for example, in glass-reinforced plastics, this hypothesis calls for experimental and theoretical verification.

Some experimental data show that the monolithicity of the system glass fiber-polymeric binder is lost during loading [66]. This is shown by the variation in the modulus of elasticity. Obviously, there is some lower bound of "crack formation" for glass-reinforced plastics, which depends on the nature of the material and on the external loadings.

Investigators and practitioners find it necessary to establish the stress level at which oriented plastics behave as a monolith. It is quite obvious that the presence of cracks in a material when it is in service in chemically corrosive media leads to accelerated failure of glass-reinforced plastics.

Establishing bounds within which a material behaves as a monolith as a function of external conditions is necessary for glass-reinforced plastics in order to revise the range of applicability of all formulas and methods of calculation based on the assumption of the continuity and combined functioning of fibers and binders. This is particularly important when evaluating the possibility of using articles made of glass-reinforced plastics for long-term service in chemical equipment and pipelines, where the structure must not only be strong, but also gas-tight.

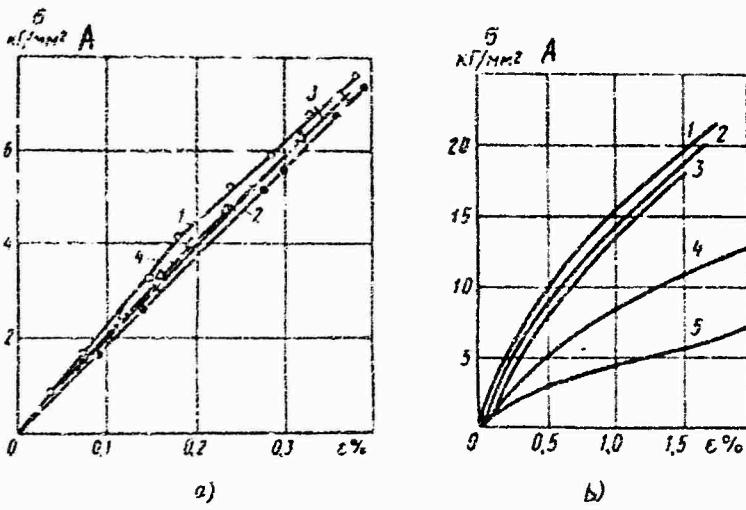


Fig. 3. Strain curves:

a -- oriented AG-4S glass-reinforced plastic with mutually perpendicular lay-up of fibers in the 1:1 ratio at  $t = 18^\circ \text{ C}$  (curve 1),  $t = 60^\circ \text{ C}$  (curve 2),  $t = 120^\circ \text{ C}$  (curve 3), and at  $t = 150^\circ \text{ C}$  (curve 4)

b -- glass-reinforced textolite using epoxy-phenolic binder at  $t = 18^\circ \text{ C}$  (curve 1),  $t = 60^\circ \text{ C}$  (curve 2),  $t = 100^\circ \text{ C}$  (curve 3),  $t = 125^\circ \text{ C}$  (curve 4), and  $t = 150^\circ \text{ C}$  (curve 5)

KEY: A --  $\sigma$ ,  $\text{kg}/\text{mm}^2$

#### Time Dependence of the Strength of Reinforced Plastics

At the present time there is a fully developed theory of the strength of polymers and polymer-based materials. The strength theory was formulated in the works of S. N. Zhurkov and coworkers and was further revised and elaborated in later studies by G. M. Bartenev, V. Ye. Gul', Yu. S. Zuyev, and other scientists.

Analysis of existing theories of long-term strength and their generalization and critical scrutiny were conducted in recent years in a number of fundamental works [7, 25, 17]. For this reason, we will limit ourselves only to a brief presentation of the essentials of the strength theory, stressing the results of the study of how reinforced plastics behave in chemically corrosive media, and also features of the strength of materials associated with external factors of chemical technology.

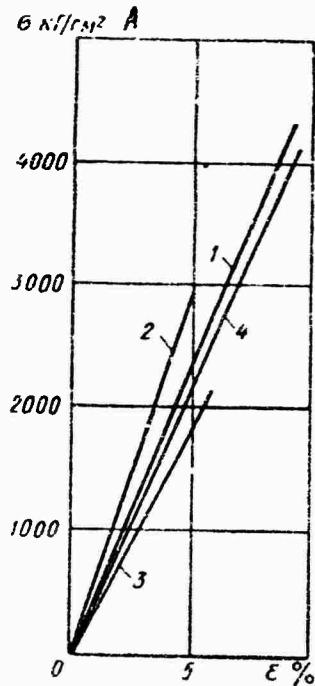


Fig. 4. Strain curves of samples of EP-32-301 glass-reinforced textolite (loading rate 6 mm/min):

- 1 -- control
  - 2 -- after exposure in 30%  $\text{H}_2\text{SO}_4$  for 1800 hr  
(room temperature, stress 600  $\text{kg/cm}^2$ )
  - 3 -- after exposure in 20%  $\text{H}_2\text{SO}_4$   
for 5000 hr (room temperature, stress 650  $\text{kg/cm}^2$ )
  - 4 -- after exposure in 30%  $\text{H}_2\text{SO}_4$   
for 1000 hr (50° C, not loaded)
- KEY: A --  $\sigma$ ,  $\text{kg/cm}^2$

One of the fundamental properties of the strength of solids is the time dependence of strength. The time dependence of strength is expressed by the fact that a specimen can fail at any stress after a certain time interval has elapsed. This time to failure of a specimen exposed to a constant stress ( $\sigma$ ) was called "longevity" ( $\tau_{cr}$ ). The dependence of  $\tau_{cr}$  on stress in exothermal conditions be represented as the exponential function

$$\tau_{cr} = Ae^{-\alpha\sigma}, \quad (1)$$

where A and  $\alpha$  are experimental coefficients typical of each material.

Equation (1) has not gained adequate practical application, since thus far sufficient data on the numerical values of coefficients A and  $\alpha$  have not yet been accumulated for most polymers.

Fairly recently, A and  $\alpha$  were determined for the following materials [20]:

	A in sec	$\alpha$ in cm/sec
Textolite PT-1 .....	$7.3 \cdot 10^6$	$0.84 \cdot 10^2$
Glass-reinforced voloknit AG-4, pressed		
at $130^\circ C$ .....	$60 \cdot 10^3$	$0.24 \cdot 10^2$
at $170^\circ C$ .....	$10 \cdot 10^3$	$0.93 \cdot 10^2$
Black voloknit:		
load is applied parallel to the plunger		
movement .....	$2.1 \cdot 10^4$	$0.81 \cdot 10^2$
load is applied perpendicular to the		
plunger pressure .....	$4.5 \cdot 10^2$	$0.61 \cdot 10^2$

P. M. Kozlov [37] suggested an interesting method of the indirect determination of A and  $\alpha$  based on creep curves. This undoubtedly broadens the designer's options.

However, as we were able to establish, the parameters A and  $\alpha$  depend strongly on the nature of the ambient environment and also on the conditions and operating regime of articles.

The time theory of strength establishes that the failure of solids takes place not only due to loading, but to a large extent due to thermal motion. Molecular and chemical bonds responsible for the strength of materials are broken due to fluctuations in thermal energy at a certain frequency [8].

Consequently, the physicomechanical concept of ultimate strength widely used in practice is an arbitrary concept and loses physical significance for polymeric materials since it is not associated with the time during which the force acts. Strength characteristics of plastics vary with

temperature and the time during which the load is applied. In the general case, the concept of the temperature-time dependence of strength is introduced.

The temperature-time dependence of the strength of solids is described by a formula of S. N. Zhurkov:

$$\tau_{cr} = \tau_0 \exp(u_0 - \gamma\sigma)/kT , \quad (2)$$

where  $\tau_{cr}$  is longevity;

$\sigma$  is stress;

$k$  is Boltzmann's constant;

$T$  is absolute temperature in °K; and

$u_0$ ,  $\tau_0$ , and  $\gamma$  are certain constants.

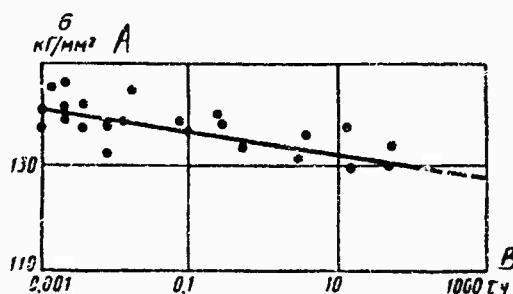


Fig. 5. Dependence of static strength on time for glass filaments

KEY: A --  $\sigma$ , kg/mm<sup>2</sup>

B --  $\tau$ , hours

As shown by S. N. Zhurkov,  $\tau_0$  is close to the period of the natural oscillations of atoms ( $10^{-12}$  to  $10^{-13}$  sec). The coefficient  $\gamma$  characterizes the variation in the potential barrier  $u_0$  (chemical bond energy) with rise in stress. The quantity  $\gamma$  depends strongly on the nature of the material. Fig. 5 presents a representative plot of the time dependence of the strength of glass filaments.

Methods of determining and calculating  $u_0$ ,  $\tau_0$ , and  $\gamma$  have been described in the works [25, 27, 73]. G. M. Bartenev [7, 8] showed that the pre-exponential multiplier  $\tau_0$  depends weakly on temperature and stress.

The temperature-time dependence of strength enables the designer to make substantiated calculations of equipment with allowance for its service time. However, this requires that  $A$  and  $\alpha$ , or  $u_0$ ,  $T_0$ , and  $\gamma$  be determined experimentally. These coefficients are determined on the basis of relatively short-term tests at high loads of specimens of the plastic under conditions close to service conditions [7, 18].

#### Effect of Corrosive Media and Temperature on the Longevity of Reinforced Plastics

A specific feature of the operation of chemical equipment and pipelines is the exposure of the material to chemically corrosive liquids. In addition, the material experiences the effect of temperature and external loading. Thus, we can speak of the simultaneous exposure to stress, temperature, and corrosive medium.

Unfortunately, most studies are limited to examining the effect on the material of the medium and temperature, without allowing for loading. For example, Table 15 presents data from tests of certain glass-reinforced plastics in water, nitric, hydrochloric, and acetic acids.

From Table 12 we can see that glass-reinforced textolites incorporating polyester and phenolic binders retain their initial strength in acid vapor after a 40-day exposure, but lose strength markedly when exposed in liquid media. However, these data are not adequate for the calculation of pressure structures; it is not clear how a material will behave under the same conditions when an external loading is present.

These tests (Table 16) show a substantial difference in the behavior of material when loaded and when not loaded. FI-1 glass-reinforced textolite, exhibiting a strength loss of only 1.2 percent when exposed in 30 percent  $H_2SO_4$  for 720 hours (30 days), failed under the same conditions when subjected to a tensile stress of  $300 \text{ kg/cm}^2$ .

Actually, on exposure to temperature processes of deformation are accelerated, and the material's longevity is reduced. Glass fiber and the binder have different coefficients of thermal expansion, which leads to a reduction of internal stresses and the formation of voids, pores, cracks, and other defects, with heating. These processes are irreversible; they facilitate the diffusion of the medium into the material. A stress applied to a material enlarges defects and accelerates the failure process. For this reason, the binder must exhibit increased chemical resistance to the medium and good adhesion to the reinforcing fibers in order to impart reliability and longevity to the material. Here it is particularly important for glass-reinforced plastics that complete polycondensation of the binder takes place, since impurities of free components and the initial low-molecular products in the binder considerably lower the chemical resistance of materials.

TABLE 15. ULTIMATE STRENGTH OF GLASS-REINFORCED PLASTICS AFTER EXPOSURE TO VAPOR AND LIQUID CORROSIVE MEDIA FOR 40 DAYS AT 20° C

1 Тип стеклопластика	2 Толщина образца в мм	3 Предел прочности при изгибе кон- тrolных образцов в кг/см <sup>2</sup>	4 Предел прочности при изгибе в кг/см <sup>2</sup> после выдержки в									
			5 парах воды	6 воде	7 парах 10%-ной азотной кислоты	8 10%-ной азотной кислоте	9 парах 10%-ной соляной кислоты	10 10%-ной соляной кислоте	11 парах уксусной кислоты (леди- нке)	12 уксусной кисло- те (ледяной)		
13 Стеклопластик ПН-1 на основе стекломатов бесщелочного состава	5,5—8,0	1225	—	826	1065	959	1312	903	640	825		
14 Стеклопластик на основе стекломатов и полизифирного связующего	1,8—2,2	1270	—	—	783	—	1110	—	1168	—		
15 Стеклотекстолит ПН-1	3,5	2285	2118	968	1459	—	2020	—	874	—		
16 Стеклопластик К-6 типа глякрезит	3,2—3,6	977	—	923	985	680	768	732	923	787		
17 Стеклотекстолит КАСТ-В	4,2	2880	2665	2370	2526	—	2712	—	—	—		
18 Стеклотекстолит КАСТ	1,2	2816	2751	2070	2409	1769	2756	874	1852	2642		

KEY: 1 -- Type of glass-reinforced plastics  
 2 -- Specimen thickness in mm  
 3 -- Ultimate strength in flexion of control specimens in kg/cm<sup>2</sup>  
 4 -- Ultimate strength in flexion in kg/cm<sup>2</sup> after exposure in media listed  
 5 -- water vapor  
 6 -- water  
 7 -- vapor of 10% nitric acid  
 8 -- 10% nitric acid  
 9 -- vapor of 10% hydrochloric acid  
 10 -- 10% hydrochloric acid  
 11 -- vapor of acetic acid (glacial)  
 12 -- acetic acid (glacial)  
 /KEY continued on following page/

KEY / to TABLE 15 on preceding page, continued<sub>/</sub>:

- 13 -- PN-1 glass-reinforced plastic based on nonalkaline-composition glass mats
- 14 -- Glass-reinforced plastic based on glass mats and polyester binder
- 15 -- PN-1 glass-reinforced textolite
- 16 -- K-6 glass-reinforced plastic of the glakrezit type
- 17 -- KAST-V glass-reinforced textolite
- 18 -- KAST glass-reinforced textolite

TABLE 16. RESULTS OF TEXTING GLASS-REINFORCED PLASTICS IN STRESSED AND UNSTRESSED STATES AT 50° C

<sup>1</sup> Материал	<sup>2</sup> Среда	<sup>3</sup> Напряжение в кг/см <sup>2</sup>	<sup>4</sup> Время испы- тания в ч	<sup>5</sup> Исходная предел проч- ности в кг/см <sup>2</sup>	<sup>6</sup> Снижение предела прочности в %
<sup>7</sup> Стеклотекстолит ЭФ-32-301 (эпоксидно-фенольное связующее и стеклоткань бесцелочного состава)	<sup>8</sup> 3%-ный рас- твор H <sub>2</sub> SO <sub>4</sub>	875 345 0	340 290 420	4180 4180 4350	<sup>16</sup> Разрыв 32,0 16,8
<sup>9</sup> Стеклотекстолит ЭФ-32-301 (эпоксидно-фенольное связующее и стеклоткань бесцелочного состава)	<sup>10</sup> 30%-ный рас- твор H <sub>2</sub> SO <sub>4</sub>	680 0 840 0	512 520 240 240	4080 4350 4080 4350	<sup>16</sup> Разрыв 64,3 41,2 29,1
<sup>11</sup> Стеклотекстолит ЭФ-32-301 (эпоксидно-фенольное связующее и стеклоткань бесцелочного состава)	<sup>12</sup> 20%-ный рас- твор NaOH	1250 0	260 480	4350 4350	<sup>16</sup> Разрыв 61,0
<sup>13</sup> Стеклотекстолит ПН-1 (полизифирная смола и стеклоткань щелочного состава)	<sup>14</sup> 30%-ный рас- твор NaOH	620 0	2 140	3330 3330	<sup>16</sup> Разрыв 42,9
<sup>15</sup> Стеклотекстолит ФЛ-1 (фурановая смола и стеклоткань щелочного состава)	<sup>10</sup> 30%-ный рас- твор H <sub>2</sub> SO <sub>4</sub>	300 0	75 720	1670 1670	<sup>16</sup> Разрыв 1,2

/KEY to TABLE 16 given on following page<sub>/</sub>

KEY [to TABLE 16 on preceding page]:

- 1 -- Material
- 2 -- Medium
- 3 -- Stress in kg/cm<sup>2</sup>
- 4 -- Test time in hours
- 5 -- Initial ultimate strength in kg/cm<sup>2</sup>
- 6 -- Reduction in ultimate strength in %
- 7 -- EF-32-301 glass-reinforced textolite  
(epoxy-phenolic binder and nonalkaline-composition glass cloth)
- 8 -- 3% H<sub>2</sub>SC<sub>4</sub> solution
- 9 -- EF-32-301 glass-reinforced textolite  
(epoxy-phenolic binder and nonalkaline-composition glass cloth)
- 10 -- 30% H<sub>2</sub>SO<sub>4</sub> solution
- 11 -- EF-32-301 glass-reinforced textolite  
(epoxy-phenolic binder and nonalkaline-composition glass cloth)
- 12 -- 20% NaOH solution
- 13 -- PN-1 glass-reinforced textolite (polyester resin and alkaline-composition glass cloth)
- 14 -- 30% NaOH solution
- 15 -- FL-1 glass-reinforced textolite (furan resin and alkaline-composition glass cloth)
- 16 -- Rupture

Unfortunately, the lack of adequate data on the longevity of reinforced plastics in general, especially in specific conditions of the service of chemical equipment, led to different approximate methods of calculation and the introduction of the so-called "safety factors," which in some cases range from 1.5 to 20 [82, 99].

Nonetheless, available material enables us to trace quite specific correlations, and ways of investigating and calculating the longevity of certain reinforced plastics under actual service conditions of chemical equipment.

Fig. 6 presents results of tests made of the longevity of EF-32-301 glass-reinforced textolite in sulfuric acid and in caustic soda when exposed to constant tensile stress.

As we can see, experimental data approximated in the coordinates  $\sigma - \lg \tau$  fit well with a linear function. Similar results were obtained also in tests made of glass-reinforced textolites incorporating PN-1 polyester binder (Fig. 7).

Therefore, at constant temperature ( $t = \text{const}$ ), the longevity of reinforced plastics can be represented by the exponential function (1), where the parameter  $\alpha$  is determined by the slope of the longevity line. The parallelity of the longevity lines for each medium indicates that the parameter  $\alpha$  does not depend on the concentration of the medium. The shift of the longevity lines as a function of the concentration of the medium will be determined by parameter A. Experiments conducted with the same materials and in the same media, but at different temperatures showed that the linear function  $\sigma - \lg \tau$  is valid over a wide temperature range. The nature of the deformation of a material is not reflected in the character of the longevity lines. Figs. 8 and 9 present results of studies made of glass-reinforced plastics in liquid media when exposed to a constant flexural stress. In this case, experimental data are also described by exponential equation (1). The parallelity of the longevity lines as a function of concentration makes it possible, when investigating the effect of temperature on the longevity of reinforced plastics, to conduct studies at some single concentration. Figs. 10, 11, and 12 give the results of an investigation of the longevity of glass-reinforced plastics at different temperatures in sulfuric acid and in sodium hydroxide on exposure to tensile stress.

Analysis of these data shows that the longevity lines for different temperatures converge at the same pole, which is in agreement with the data of S. N. Zhurkov obtained for other materials tested in air. Therefore, the temperature-time dependence of the strength of reinforced plastics in corrosive media is described by an equation formally akin to S. N. Zhurkov's formula (2). However, the parameters  $\tau_0$ ,  $u_0$ , and  $\gamma$  are completely different in physical significance and numerical value. For example, according to S. N. Zhurkov the parameter  $\tau_0$  is independent and corresponds to the frequency of the natural oscillations of atoms ( $10^{-12}$  to  $10^{-13}$  sec.).

In our own and other investigations [15, 14, 75] of longevity in liquid media, the numerical values of parameter  $\gamma$  were found to differ, for example, of the order of  $10^{-2}$ ,  $10^{-6}$ , and  $10^{-8}$  sec. Therefore, the parameter  $\tau_0$  is at least dependent on the ambient environment, whose effect was virtually neglected in S. N. Zhurkov's investigations.

At constant temperature ( $t = \text{const}$ ), equation (2) takes on the form of equation (1), where  $A = \tau_0 \exp(u_0/kT)$  and  $\alpha = \gamma/kT$ .

Table 17 presents several experimental values of parameter A.

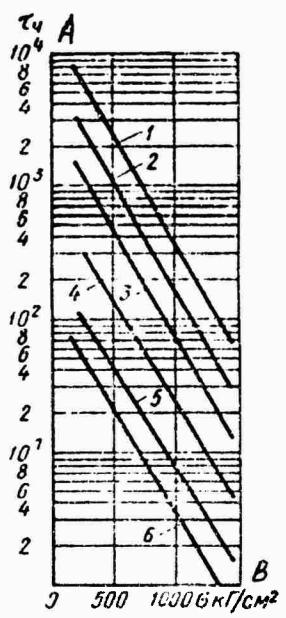


Fig. 6. Dependence of longevity of EF-32-301 glass-reinforced textolite on concentration of sulfuric acid ( $t = 90^\circ \text{ C}$ ) and sodium hydroxide ( $t = 50^\circ \text{ C}$ ):  
 1 ---  $\text{NaOH} -- 20\%$   
 2 ---  $\text{NaOH} -- 1\%$   
 3 ---  $\text{NaOH} -- 10\%$   
 4 ---  $\text{H}_2\text{SO}_4 -- 60\%$   
 5 ---  $\text{H}_2\text{SO}_4 -- 30\%$   
 6 ---  $\text{H}_2\text{SO}_4 -- 3\%$

KEY: A ---  $\tau$ , hours  
 B ---  $\sigma$ ,  $\text{kg}/\text{cm}^2$

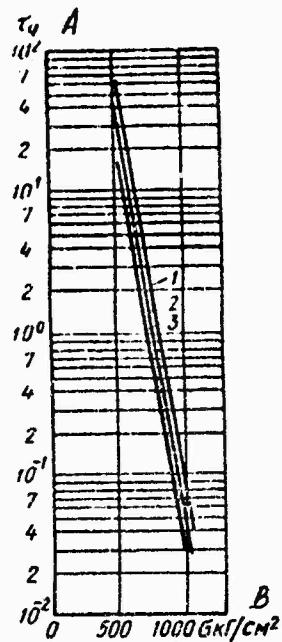


Fig. 7. Dependence of longevity of glass-reinforced textolite incorporating PN-1 polyester resin on sulfuric acid concentration ( $t = 40^\circ \text{ C}$ ):  
 1 --- 60%  
 2 --- 30%  
 3 --- 3%  
 KEY: A ---  $\tau$ , hours  
 B ---  $\sigma$ ,  $\text{kg}/\text{cm}^2$

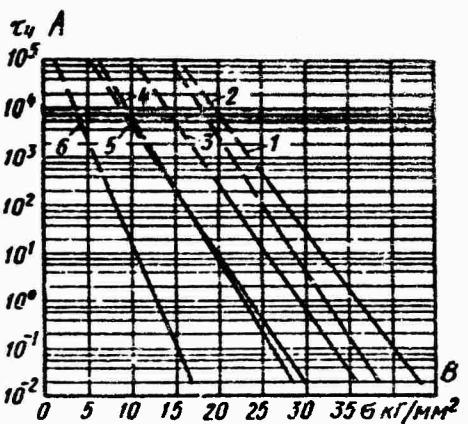


Fig. 8. Longevity curves for glass-reinforced plastics based on PN-1 resin and ASTT (b) -S<sub>2</sub> cloth with satin weave  
8/3 [22]:

- 1 and 3 -- with treatment using a 5% GVS-9 solution, testing in air and in sea water
- 2 and 4 -- with treatment using a 5% GVS-9 solution (with stress concentrator), testing in air and in sea water
- 5 and 6 -- with treatment using wax sizing agent, testing in air and in sea water

KEY: A --  $\tau$ , hours  
B --  $\sigma$ , kg/mm<sup>2</sup>

The convergence of the longevity lines at the same pole (cf. Fig. 12) shows that the parameters  $\alpha$  and A vary monotonely, dependent in the general case on the properties of the material, temperature, and the concentration of the ambient environment. As shown by experiments [77], for some glass-reinforced plastics the parameter  $\alpha$  depends on temperature and the nature of the corrosive medium, but does not depend on its concentration. The coefficient A depends on the nature of the corrosive medium, its concentration, and temperature, for specific glass-reinforced plastics.

In the general case, the longevity of materials subjected to the combined exposure of corrosive medium, temperature, and loading is a complex function of five arguments: the nature of the material M, nature of the corrosive medium D, its concentration C, temperature t, and stress  $\sigma$ , that is,  $\tau = \psi(M, C, D, t, \sigma)$ . This then accounts for the difficulty of the experimental and theoretical determinations of the longevity of plastics under conditions of the operation of chemical equipment and pipelines. [Text pages 44-45 are missing.]

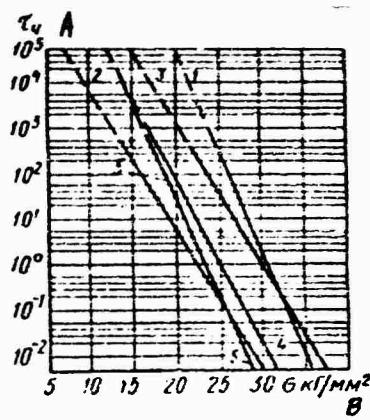


Fig. 9. Longevity curves for glass-reinforced plastics at  $t = 14^\circ \text{ C}$  [22]:  
 1 and 2 -- incorporating binder 911 (blend of polyester acrylates MGF-9 and TMGF-11) with testing in air and sea water  
 3, 4, and 5 -- incorporating PN-3 resin with testing in air, in sea water, and in fresh water  
 KEY: A --  $\tau$ , hours  
 B --  $\sigma$ , kg/mm<sup>2</sup>

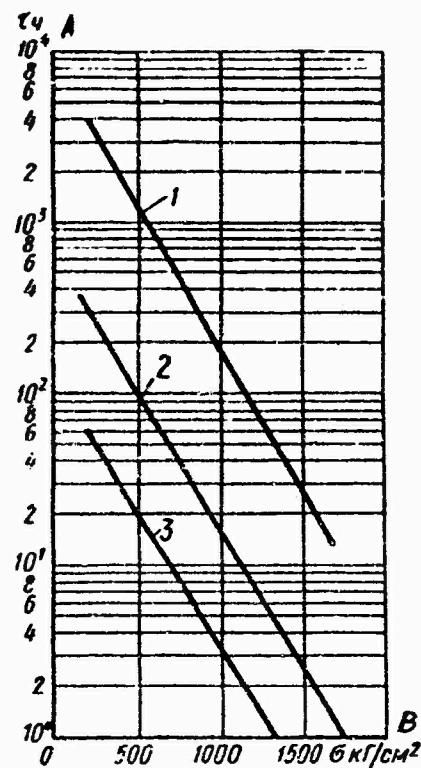


Fig. 10. Dependence of longevity of EP-32-301 glass-reinforced textolite on temperature in 3%  $\text{H}_2\text{SO}_4$  solution:  
 1 -- at  $t = 50^\circ \text{ C}$   
 2 -- at  $t = 70^\circ \text{ C}$   
 3 -- at  $t = 90^\circ \text{ C}$   
 KEY: A --  $\tau$ , hours  
 B --  $\sigma$ , kg/cm<sup>2</sup>

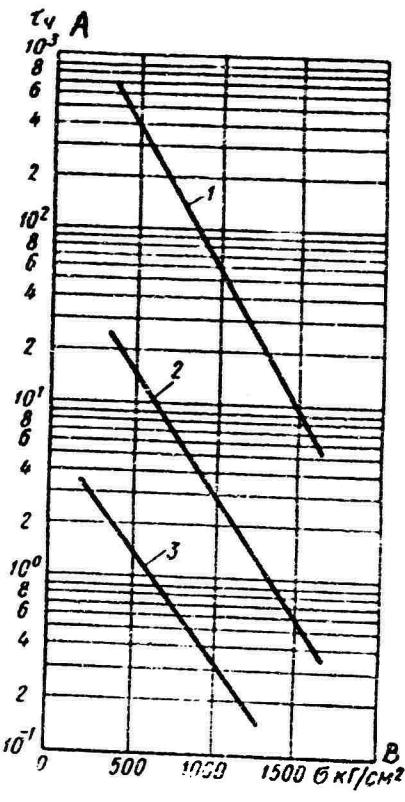


Fig. 11. Dependence of longevity of EF-32-301 glass-reinforced textolite on temperature in 10% NaOH solution:

- 1 -- at  $t = 50^\circ \text{ C}$
- 2 -- at  $t = 70^\circ \text{ C}$
- 3 -- at  $t = 90^\circ \text{ C}$

KEY: A --  $\sigma$ , hours  
B --  $\tau$ ,  $\text{kg}/\text{cm}^2$

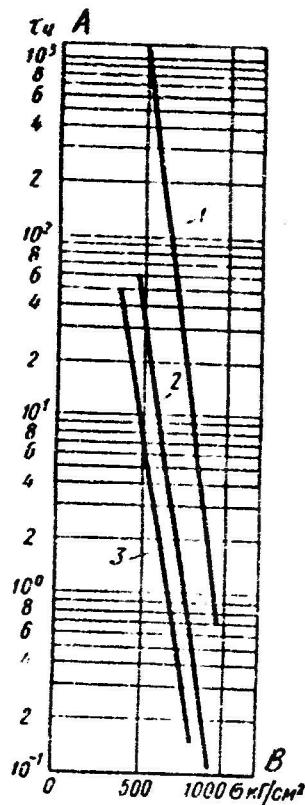


Fig. 12. Dependence of longevity of glass-reinforced textolite incorporating PN-1 resin on temperature in 30%  $\text{H}_2\text{SO}_4$  solution:

- 1 -- at  $t = 50^\circ \text{ C}$
- 2 -- at  $t = 70^\circ \text{ C}$
- 3 -- at  $t = 90^\circ \text{ C}$

KEY: A --  $\sigma$ , hours  
B --  $\tau$ ,  $\text{kg}/\text{cm}^2$

Text pages 44-45 are missing . . . case, quite naturally we must regard longevity as referring to the period of the continuous operation of the material or article at constant load (hydrostatic pressure) until gas-tightness is disturbed.

In the general case, the longevity of a material must be regarded as the time interval during which its properties measure up to the technical service norms under given conditions. Examination of glass-reinforced plastic pipes (with reference to their gas-tightness) incorporating different binders and different fabrication procedures made it possible to establish that in these cases as well, the time dependence of strength in the tangential direction  $\sigma_t$  is manifested (Figs. 15 and 16) [1, 18].

### Creep of Reinforced Plastics

If to a specimen of a polymeric material a constant stress is applied, then a rise in deformation, that is, creep, can be observed with the course of time. The creep phenomenon is highly typical of polymeric materials and is detected even at room temperature. Though the deformations building up during the creep of reinforced plastics are not as great as in thermo-setting plastics, this phenomenon cannot be ignored in designing machines and equipment made of reinforced plastics.

A study of the creep curves of reinforced plastics in tension showed that initially a rapid rise in deformation with time is observed -- the stage of nonsteady-state creep; later, the creep rate remains virtually constant or gradually decreases until rupture sets in [51].

The initial creep state at room temperature was studied for textolite, and KAST-V and SVAM glass-reinforced textolite [51]. Experiments showed that creep deformation increases with stress  $\sigma$ ; it depends heavily on specimen orientation, reaching a maximum for the direction of least stiffness (for  $\phi = 45^\circ$ ). Fig. 17 presents the results of experiments conducted by A. M. Zhukov and S. D. Vyalukhina [32] on STER-1-30 glass-reinforced textolite for directions along the base ( $\phi = 0^\circ$ ), along the weft ( $\phi = 90^\circ$ ), and along the intermediate layer ( $\phi = 40^\circ$ ). From these data it is clear that owing to the property-anisotropy of reinforced plastics, creep deformation depends on orientation; it is a minimum along the axes of elastic symmetry and a maximum in the intermediate directions. This is attributed to the fact that the reinforcing fiber is more elastic than the binder.

In describing the creep process, either a linear function of the creep rate, which does not agree with experimental data, has been proposed, or an exponential function. The latter fits the initial section of the creep curve (this section is of least interest when estimating the behavior of a structure in its long-term service conditions). Most experimental studies [27, 51] showed that in steady-state creep the stress function of creep and creep per se is closest to the exponential. At a constant temperature, the creep rate  $v$  is described by the equation

$$v = D e^{-\beta v}, \quad (3)$$

similar to equation (1), where  $D$  and  $\beta$  are experimental parameters.

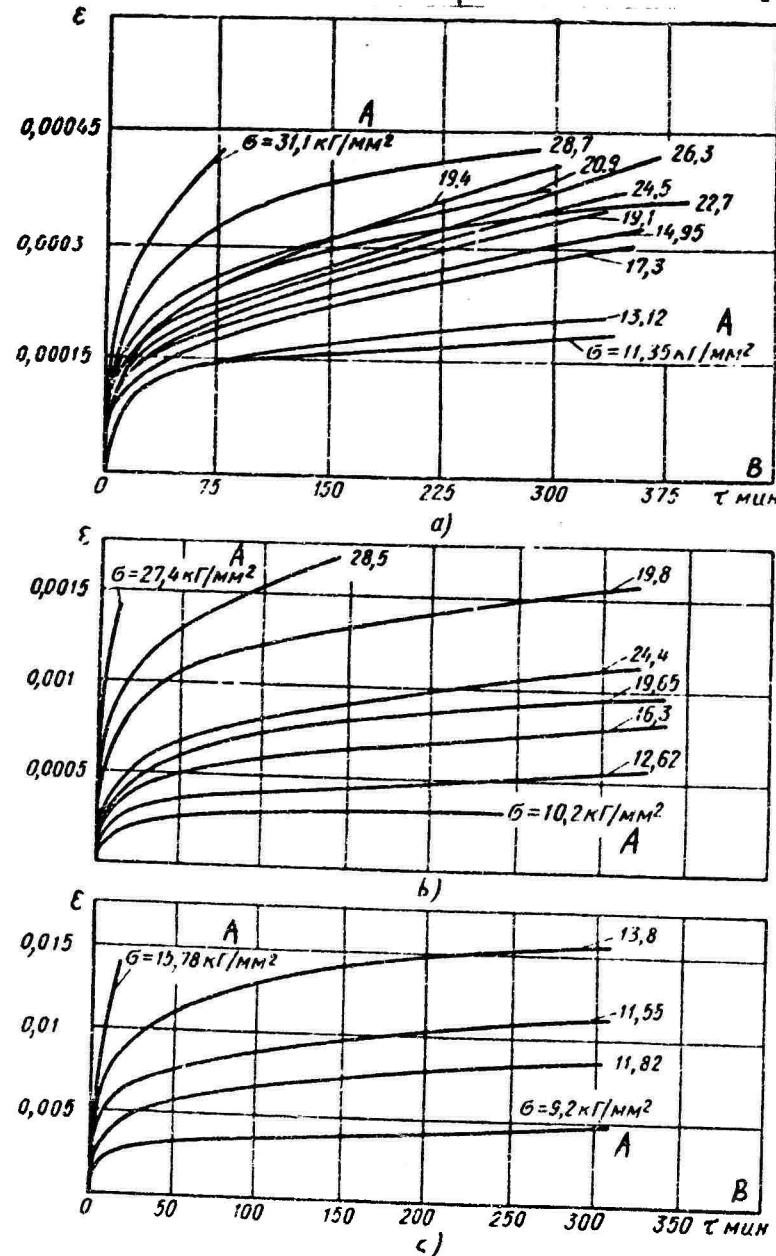


Fig. 17. Creep curves of STER-1 glass-reinforced textolite:

a -- for  $\varphi = 0^\circ$     b -- for  $\varphi = 90^\circ$     c -- for  $\varphi = 40^\circ$   
 KEY: A --  $\text{kg/mm}^2$     B -- minutes

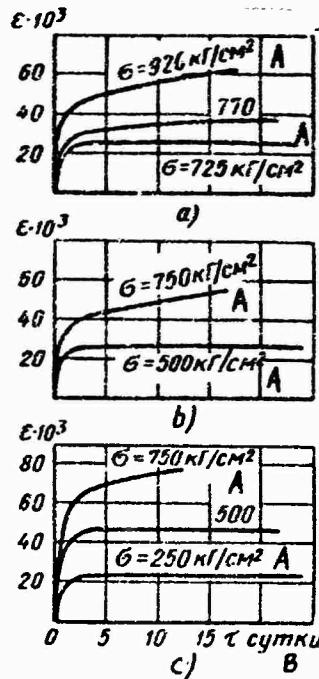


Fig. 18. Creep curves of DSP-V delta-wood at the following temperatures:  
 a --  $20^\circ \text{ C}$    b --  $50^\circ \text{ C}$    c --  $100^\circ \text{ C}$   
 KEY: A --  $\text{kg/cm}^2$    B -- days

Fig. 18 presents creep curves for reinforced plastics obtained in testing delta-wood [9]. From an analysis of these curves it is clear that temperature has a large effect on creep, where for each temperature there are certain stress values for which the creep rate is virtually zero. The stress at which creep deformation has its maximum (the rate of steady-state creep is zero) is sometimes called the "threshold" stress [37].

The inception of "threshold" stress is associated with the structuring of polymers.

All these data pertain to experiments conducted in air with reinforced plastics. Still, the behavior of materials in liquid chemically corrosive media must be of interest to designers of chemical equipment. Investigations of the creep of certain types of glass-reinforced textolites in acids and alkalies showed that the medium has a very strong effect on creep.

Figs. 19-22 present the creep curves of EF-32-301 glass-reinforced textolite and FN-1 glass-reinforced textolite when they were studied in sulfuric acid, sodium hydroxide, and distilled water. As we can see, creep occurs in two stages:

nonsteady-state creep characterized by a steep rise in the curve; and

the stage with steady-state creep rate -- the shallow section of the curve.

In semilogarithmic coordinates, the buildup of deformation with time obeys the linear law  $\epsilon = \epsilon_1 + v \lg \tau$ . Therefore,  $\epsilon$  can be determined from the equation

$$\epsilon = \epsilon_1 + v \lg \tau, \quad (4)$$

where  $\epsilon_1$  is deformation per unit time;

$v = (\epsilon - \epsilon_1)/\lg \tau$  is the creep rate characterized by the slope of the line  $\epsilon - \lg \tau$ .

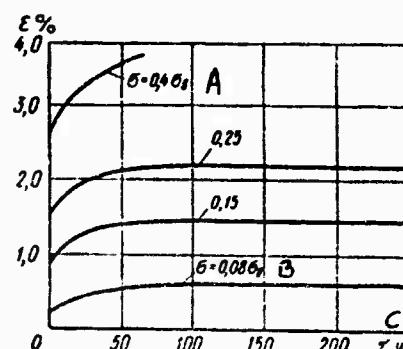


Fig. 19. Creep curves of glass-reinforced textolite based on EF-32-301 resin in 30 percent  $H_2SO_4$  at  $50^\circ C$

KEY: A --  $\sigma = 0.4 \sigma_f$   
B --  $\sigma = 0.08 \sigma_f$   
C --  $\tau$ , hours

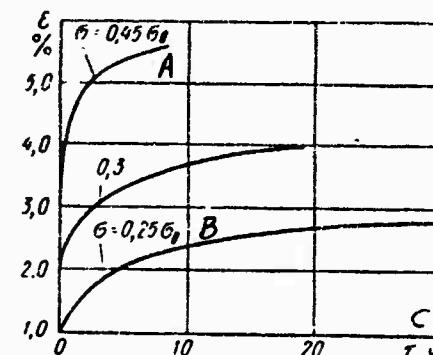


Fig. 20. Creep curves of glass-reinforced textolite with EF-32-301 resin in 10 percent NaOH at  $50^\circ C$

KEY: A --  $\sigma = 0.45 \sigma_f$   
B --  $\sigma = 0.25 \sigma_f$   
C --  $\tau$ , hours

It must be borne in mind that for  $\tau = 0$ , equation (4) tends to a finite value; this is not physically meaningful, since in this case the deformation is equal to the instantaneous deformation.

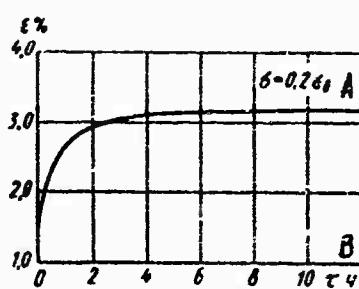


Fig. 21. Creep curves of glass-reinforced textolite with PN-1 resin in 60 percent  $H_2SO_4$  at  $60^\circ C$

KEY: A —  $\sigma = 0.2 \sigma_f$   
B —  $\tau$ , hours

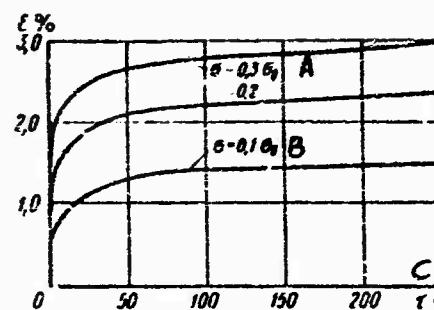


Fig. 22. Creep curves of glass-reinforced textolite with EF-32-301 resin in distilled water at  $50^\circ C$

KEY: A —  $\sigma = 0.3 \sigma_f$   
B —  $\sigma = 0.1 \sigma_f$   
C —  $\tau$ , hours

Analysis of results obtained in a study of the creep of glass-reinforced textolites in corrosive media affords the conclusion that instantaneous deformations and creep rates increase with the corrosiveness of a medium (Table 18). The creep rate in sodium hydroxide is greater than in sulfuric acid for the same temperatures and stresses, since sodium hydroxide is stronger reagent for glass-reinforced plastics than is sulfuric acid. The stress dependence of the creep rate in semilogarithmic coordinates  $\sigma - \lg v$  is represented by a straight line (Fig. 23), that is, even in corrosive media creep is described by equation (3).

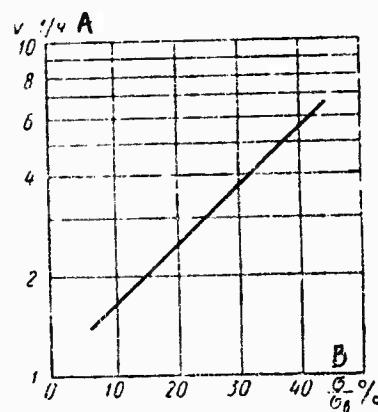


Fig. 23. Dependence of creep rate of glass-reinforced textolite based on EF-32-301 resin on the stress ratio (30 percent  $H_2SO_4$ ,  $t = 50^\circ C$ )

KEY: A —  $hr^{-1}$       B —  $\sigma/\sigma_f$

If we know the parameters  $A$  and  $\alpha$ , the earlier-presented equations (1) and (2) can be used in the calculations of structures, however here we must also take into account the deformations developing in time. When fitting together structural members, it is mandatory to specify and determine the allowable deformations for the given service time. An ideal case here can be a calculation based on the "threshold" stresses to which a specific deformation corresponds. In this case the allowable stress  $\sigma_{al}$  [ $al = \text{allowable}$ ] must satisfy the condition

$$\sigma_{al} \leq \sigma_h - E_e (\epsilon_{lim} - \epsilon_{el}) \quad (5)$$

where  $\sigma_h$  is the stress at which creep deformation reaches its limiting value ("threshold" stress);  
 $E_e$  is the modulus of high elasticity;  
 $\epsilon_{lim}$  is the limiting deformation; and  
 $\epsilon_{el} = \sigma/E_1$  is the instantaneously elastic deformation ( $E_1$  is the modulus of instantaneous elasticity).

The maximum  $\sigma_h$  will occur for  $\epsilon_{lim} = \epsilon_p$  ( $\epsilon_p$  is the deformation determined from the "elongation-compression" curve for which the stress reaches its maximum).

Experience in the service of polymeric articles showed that they function successively at stresses much higher than  $\sigma_h$ , given the condition that their deformations during the period of exposure to external loading do not exceed allowable values based on design considerations (the stability of the form is not disturbed). Therefore, we must employ a more general method of calculation based on allowable deformations and also based on strength conditions. The following solution to the problem has been suggested [37]. Suppose that the service period  $\tau_e$  and the allowable deformation during this time  $\epsilon_{al}$  have been specified. In this case, the flow rate of the material  $v_{fl}$  must satisfy the condition

$$v_{fl} \leq \epsilon_{al}/\tau_e . \quad (6)$$

To solve this equation, we must know how the flow rate of the material  $v_{fl}$  depends on the stress  $\sigma$ ; in the simplest case for service in air and at temperature  $t = \text{const}$

$$v_{fl} = f(\sigma) . \quad (7)$$

TABLE 18. DEFORMATION AND CREEP RATE OF EP-32-301 GLASS-REINFORCED PLASTIC FOR DIFFERENT TEMPERATURES OF CORROSIVE MEDIA

1 Напря- жение в % от предела прочно- сти	2 Мгновенная деформация в % при температуре в °C		3 Скорость ползучести 1/ч при температуре в °C		4 Деформация в мо- мент разрушения в % при темпе- ратуре в °C	
	50	90	50	90	50	90
<i>5 30%-ный раствор H<sub>2</sub>SO<sub>4</sub></i>						
8	0,27	—	0,151	—	1,0	—
25	1,55	1,97	0,3	0,54	2,5	2,7
40	2,37	—	0,55	—	3,65	—
<i>6 60%-ный раствор H<sub>2</sub>SO<sub>4</sub></i>						
20	—	0,93	—	0,1	—	1,5
25	—	1,09	—	0,18	—	1,45
35	—	1,9	—	0,52	—	2,6
40	2,22	—	0,226	—	3,5	—
<i>7 1%-ный раствор NaOH</i>						
15	0,1	0,91	0,502	0,752	1,7	2,5
18	1,35	—	0,520	—	2,6	—
25	1,43	—	0,572	—	2,7	—
30	—	2,0	—	0,995	—	4,2
<i>8 10%-ный раствор NaOH</i>						
15	0,5	—	0,351	—	1,4	—
25	1,56	2,55	0,402	1,682	2,45	4,25
30	2,3	—	0,45	—	3,15	—
35	—	3,18	—	2,31	—	5,3
<i>9 10%-ный раствор NaOH (образцы ориентированы вдоль утка)</i>						
25	1,08	—	0,948	—	2,85	—
30	2,0	—	1,000	—	3,9	—
45	3,22	—	1,152	—	5,5	—
<i>10 Дистиллированная вода</i>						
15	0,55	—	0,3	—	—	—
20	0,94	—	0,45	—	—	—
30	1,25	—	0,5	—	—	—

KEY: 1 — Stress in % of ultimate strength

2 — Instantaneous deformation in %

at listed temperature in °C

3 — Creep rate in hr<sup>-1</sup> at listed tem-  
perature in °C

4 — Deformation at moment of failure  
in % at listed temperature in °C

KEY concluded on follow-  
ing page

KEY /to TABLE 18 given on the preceding page/:

- 5 — 30 percent  $H_2SO_4$  solution
- 6 — 60 percent  $H_2SO_4$  solution
- 7 — 1 percent NaOH solution
- 8 — 10 percent NaOH solution
- 9 — 10 percent NaOH solution (specimens are oriented along the weft)
- 10 — Distilled water

However, the flow rate of plastics in conditions typical of the service of chemical equipment will depend not only on stress, but also on the kind of corrosive medium D, its concentration C, and temperature t:

$$v_{fl} = \psi(D, C, t, \sigma). \quad (8)$$

There is some information on the stress and temperature dependence of flow rate [38]. However, data on the flow rate as a function of the nature of the corrosive medium and its concentration are virtually absent. This hinders the use of formula (6) to calculate the flow rate in designing chemical equipment. Available experimental material on the creep of individual kinds of glass-reinforced plastics in corrosive media enables us to calculate the creep (flow) rate for them, however this material is inadequate for any final generalizations and conclusions.

Data obtained for glass-reinforced plastics show that in the most severe conditions when the failure of specimens occurs in an extremely short time, even at the moment of failure deformations amount to only 3-5 percent. The total deformation of glass-reinforced plastics must be 2.2 percent in air, for example, at a stress that is 40 percent of the tensile strength and at a temperature of 90° C after 100,000 hours. Therefore, in engineering practice when calculating structures to be made of glass-reinforced plastics for long-term service in liquid media at moderate stresses of the order of 10-30 percent of the ultimate strength, and also in gaseous media at higher stresses, the creep need not be taken into account for individual glass-reinforced plastics. At high loads, determining creep deformations requires the use of functions obtained on the basis of elastic prehistory theory [9, 51, 65].

#### Behavior of Reinforced Plastics in Corrosive Media

At the present time, a vast amount of statistical material has been accumulated dealing with the chemical resistance of reinforced plastics. Information on the chemical resistance of plastics is highly useful in selecting materials for specific conditions of service.

However, when evaluating information on chemical resistance given in publications, one must be cautious and critical in using it. Most researchers publishing their data do not report the method used in obtaining them and do not specify what they adopt as the criterion of chemical resistance. Some authors do not give quantitative estimates of stability and limit themselves only to quantitative estimates. Doubtless, when selecting materials for structures not experiencing high external loads, in general most such data on the chemical stability of polymers and reinforced plastics can be used with benefit.

However, the behavior of materials in a corrosive medium under load can differ widely from the behavior of unloaded material [56, 76, 77].

This appreciable difference was found even in studies of glass fibers as such in water [67]. When glass fibers were tested in a dry environment under tensile loading, surface defects and cracks closed after the load was removed and the mechanical strength of fibers was restored after a certain period of time.

But in similar studies of glass fibers in a wet medium, the moisture (surfactant medium) -- sorbing on the microcrack surfaces -- reduced the surface energy of the material. Cracks grew irreversibly. When the load was removed, the so-called adsorptive aftereffect was observed: the molecules of the medium blocked the cracks from closing and only gradually were "forced" out of the cracks. This leads only to the partial recovery of the initial mechanical strength and facilitates failure in a new loading cycle. By accelerating crack growth, surfactants can radically modify the time dependence of strength.

The failure mechanism of solids acted on by surfactant media has been closely studied and has found sufficient treatment in the literature [45].

It must be noted that in these studies surfactants were chosen that do not chemically act on the material, that is, the surfactants were chemically inert. It can be suggested that when the medium is corrosive, the failure mechanism of the material will be more complex. To clarify this, comparative experiments were conducted [76] in aqueous solutions of sulfuric acid (a surface-inactive medium) and sodium hydroxide -- a chemically active and surfactant medium. Tests were conducted in media under loading with the specimen brought to failure (longevity tests); under loading without the specimen being brought to failure, with the change in ultimate strength at rupture after exposure established; and without loading, with the change in ultimate strength at rupture established. A marked difference in the behavior of materials was found when the results obtained for different experimental conditions were compared. For example, nonloaded polyethylene in test solutions proved to be inert (chemically resistant), since its strength after being exposed in media for 720 hours (30 days) remained unchanged. But when a tensile load ( $10-24 \text{ kg/cm}^2$ ) to specimens, specimen failure was observed after 320 hours in 10 percent NaOH, after 510 hours in 1 percent NaOH, and after 800 hours in 3 percent  $\text{H}_2\text{SO}_4$ . In

this case, we can speak about the purely physical effect of the medium. Plastic deformations build up owing to the sorption of the active medium, leading to crack growth, local overstressing, and the failure of the material.

Especially diverse results can be obtained in media that are not surface-active compounds, that is, in aqueous solutions of sulfuric acid. Fig. 24 presents data of corrosion tests (without loading) of glass-reinforced textolite EF-32-301 in 3 and 30 percent solutions of sulfuric acid. Clearly, as the acid concentration is increased, its corrosive action on the material becomes intensified. Different results are obtained from tests of the same material for longevity (under tensile loading) in the same conditions (Fig. 25). Here a rise in longevity takes place with an increase in the concentration of sulfuric acid within the limits of the manifestation of its nonoxidizing properties. The explanation of the latter, in all probability, must be sought in the action of water as a surface-active compound. As the acid concentration is increased, the water content is reduced, and thus adsorption processes proceed more slowly and the longevity increases. The validity of this conclusion is confirmed by studies of polyethylene and polypropylene in sulfuric acid, where these materials reveal complete inertness when not loaded. Here also longevity increases with the acid concentration for tests under stress. Thus, for a stress of  $24 \text{ kg/cm}^2$  the longevity of polyethylene at  $60^\circ \text{ C}$  in 3 percent  $\text{H}_2\text{SO}_4$  solution is 800 hours, and 1150 hours in a 30 percent solution.

By analyzing these results, we can draw several key conclusions on the failure mechanism of plastics on exposure to corrosive media and external loading.

The failure process in the general case is complex and corrosion-adsorptional in nature (or adsorption-corrosional), that is, two processes take place at the same time: the chemical action of the medium on the material and the adsorptional decrease in strength caused by the sorption of surface-active compounds at the surfaces of microcracks (as a result, surface tension is reduced; local overstresses intensify; and the plastic deformation in these sections becomes greater). Naturally, the rates of these two processes are not the same, and in some stages one process can predominate over another. Thus, in the case when glass-reinforced textolites were tested without loading (cf. Fig. 24), processes associated with the adsorption of water do not take place and the reduction in the material's strength is determined only by the rate of the chemical reaction, that is, by the corrosiveness (concentration) of the medium. In another case (cf. Fig. 25), the rate of the adsorptive reduction in strength predominates. The rate of the chemical reaction in the above-indicated experiments with polyethylene and polypropylene in  $\text{H}_2\text{SO}_4$  and  $\text{NaOH}$  is practically equal to zero and the failure of the materials is caused only by sorptional phenomena.

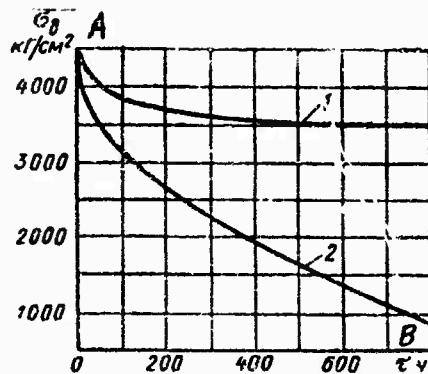


Fig. 24. Dependence of ultimate tensile strength of glass-reinforced textolite based on EF-32-301 resin on curing time (at 50° C) in sulfuric acid with the following concentration:

1 -- 3 percent    2 -- 30 percent  
KEY: A --  $\sigma_0$ , kg/cm<sup>2</sup>

B --  $\tau$ , hours

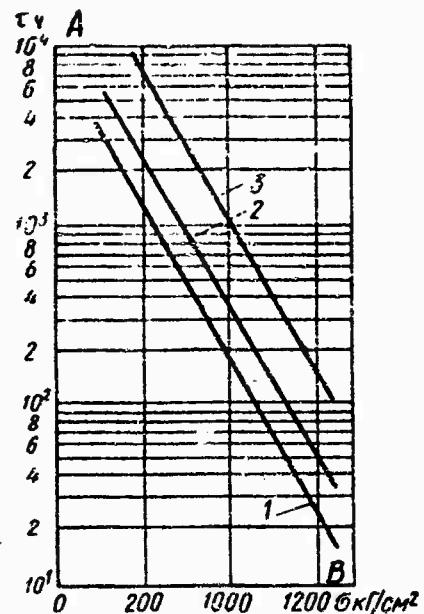


Fig. 25. Longevity curves of glass-reinforced textolite based on EF-32-301 resin (at 50° C) in sulfuric acid solutions with the following concentration:

1 -- 3 percent  
2 -- 30 percent  
3 -- 60 percent  
KEY: A --  $\tau$ , hours  
B --  $\sigma$ , kg/cm<sup>2</sup>

The failure of stressed material on exposure to a medium takes place not throughout the volume, but only in regions with the largest defects, cracks, and so on, where the intensive penetration of the medium takes place and where surface-active compounds are sorbed. This conclusion is confirmed by the fact that with repeated failure of individual parts already failed in testing the specimen for longevity, in all cases ultimate strength values were obtained that are much larger than the stresses for which the specimen was caused to fail (Table 19).

TABLE 9. ULTIMATE RUPTURE STRENGTHS OF SPECIMENS AND PARTS OF SPECIMENS OF EP-32-301 GLASS-REINFORCED TEXTOLITE AFTER LONG-TERM EXPOSURE TO MEDIUM AND STRESS (INITIAL ULTIMATE STRENGTH OF MATERIAL -- 4350 kg/cm<sup>2</sup>)

1 Среда	2 Температура °C	3 Предел прочности с кг/см <sup>2</sup>	
		4 образца	5 части образца
Вода <sup>6</sup>	50	830	4000
1%-ный раствор NaOH <sup>7</sup>	50	1530	2210
3%-ный раствор H <sub>2</sub> SO <sub>4</sub> <sup>8</sup>	90	1125	2910
60%-ный раствор H <sub>2</sub> SO <sub>4</sub> <sup>9</sup>	90	1520	3700

KEY: 1 — Medium  
 2 — Temperature in °C  
 3 — Ultimate strength in kg/cm<sup>2</sup>  
 4 — of specimen  
 5 — of specimen part  
 6 — Water  
 7 — 1 percent NaOH solution  
 8 — 3 percent H<sub>2</sub>SO<sub>4</sub> solution  
 9 — 60 percent H<sub>2</sub>SO<sub>4</sub> solution

In selecting materials for pressure structures that function in chemically corrosive liquids, even if they do not exhibit surface activity, accounting for the results of purely corrosion tests can lead to an appreciable error, since these results cannot reproduce the true processes taking place in the stressed specimen.

#### Methods of Increasing the Longevity of Reinforced Plastics

One of the paramount methods of improving the properties of reinforced plastics is improvement of their fabrication technology and in the means of quality control. Unfortunately, most technological procedures in the fabrication of large-size articles from reinforced plastics at the present time are nearly totally based on manual labor. And this leads to the non-reproducibility of properties of articles, nonuniformity of impregnation and coating of reinforcing fibers with binder, the appearance of defects, and so on. Mechanization of molding methods, use of automation devices, and

quality control of the material in the article must enhance the reliability and longevity of the materials per se, as well as the equipment and pipelines.

Serious attention must be given to the reinforcing fibers, since it is they that generally take the pressure loading. Continuous fibers afford the highest strength. For example, glass-reinforced plastics based on glass filaments and glass roving have greater longevity.

Some literature sources [62, 80] recommend that reinforcing fibers be given preliminary tension, which enhances the operating characteristics of reinforced plastics.

Close attention must be given to preparing reinforcing fibers to receive a polymeric binder. The reinforcing material must be impregnated using vacuum, pressure, or ultrasound. During processing, the fiber is treated with wax sizers, which reduce the adhesion of the resin to the fiber. Therefore, for greater longevity and improvement in physicomechanical properties of materials, the sizer is removed and to enhance waterproofing the glass fiber is treated with special organosilicon compounds of the volan and silane types [69].

Special attention must be given to selecting the chemical composition of the reinforcing fibers -- they must have maximum chemical resistance to the medium in which the material will serve and they must also exhibit adequate mechanical strength. It must also be borne in mind that the adhesion of resin depends on the chemical composition of the fibers. Thus, the adhesion of polyester resin to alkaline-composition glass fibers which have not undergone special treatment is nearly half as great as for nonalkaline fibers.

It must also be noted that chemical resistance and thus longevity are strongly affected by the ratio of the following components: reinforcing fibers and binder. Here it must be stated that in most cases the ratios adopted, especially for glass-reinforced plastics, are not wholly satisfactory from the standpoint of their application in chemical equipment and pipelines. These ratios are dictated by the attainment of maximum strength of materials. However, in this case the concepts of "strength" and "chemical resistance" are not identical. The point is that polymeric binders have greater chemical resistance than reinforcing fibers. For example, phenol-formaldehyde resins are resistant in many mineral acids ( $H_2SO_4$  to 60 percent,  $HCl$ ,  $H_3PO_4$ , and so on), while cotton and silk fibers fail even in weak solutions of acids. The same can be said of glass fibers. Therefore, special combinations of reinforcing fibers and resins must be used for chemical equipment and pipelines. When a stressed reinforced plastics reacts with a corrosive medium, the failure process begins with the chemical action of the medium on the material's surface layers. So special attention must be given to protecting the reinforcing fibers with resin, especially after machining of the material. A more rational approach is

a multi-ply structure, and enhancing the chemical resistance of the surface in contact with the corrosive medium by depositing an additional layer of binder. The kind and quality of binder naturally play a decisive role from the standpoint of chemical resistance and longevity of reinforced plastics. From this point of view, there are broad possibilities of variation in binder selection, since the possibilities of resin synthesis are unlimited. In formulating reinforced plastics satisfying the requirements of chemical resistance and longevity, of great interest are epoxy, epoxy-phenolic, furan, epoxy-furan, modified polyester, and several other combination resins. It must be borne in mind that the type of curing agent and curing regime strongly affect the chemical resistance of certain resins.

The behavior of reinforced plastics is also determined by the shrinkage of resins during their curing. Considerable shrinkage of resins leads to a reduction in strength, a rise in porosity, and an increase in crack formation, and thus, longevity is reduced. The same effect is obtained when resins are brittle, since they crack under stress. Various industrial procedures eliminating these disadvantages can add to the longevity of a material.

One serious problem associated with the use of reinforced plastics in the building of chemical equipment is the need to ensure that the materials are gas-tight. The nonuniformity of distribution of binder and reinforcing material and their inadequate bonding increase porosity for service under pressure, which leads to the loss of gas-tightness. These disadvantages can be eliminated by selecting a resin with specific viscosity and shrinkage, choosing the technological curing regime, using appropriate sizers to enhance the wettability of fibers and increase adhesion, and the application of postforming in molding, which promotes the removal of volatiles and the consolidation of article walls. This improves article quality but does not wholly solve the problem of gas-tightness. Good results were obtained by using multi-ply structures [32] in which the internal layer in contact with the corrosive medium imparts gas-tightness and chemical stability to the medium, and the outer layer bears the pressure load. Combinations of materials are used for this purpose. The favorable effect can be attained also by technological means during fabrication. For example, by centrifugal molding of bodies of revolution one can obtain an internal layer consisting wholly of binder or an internal layer that is binder-enriched.

Noteworthy is the possibility of obtaining articles made of stressed glass-reinforced plastics. Impregnated glass fibers are wound on a mandrel, which is expanded prior to the gelatinization of the resin and remains in this state until the binder has fully cured. In the article made by this means, the resin can be under the effect of compressive loads. Here the compatibility factor of the reinforcement and resin, gas-tightness, and longevity will be increased.

Pipes and equipment can be made gas-tight by using film materials for internal lining -- polyvinylchloride, polyethylene, polypropylene, sealants,

and the like. This makes it possible to use materials that are in less short supply as the pressure framework. At the present time, a technology for producing biplastics and equipment made therefrom has been developed [64]. These materials are produced on the basis of inexpensive polyester glass-reinforced materials and chemically resistant thermosetting plastics and polytetrafluoroethylene. Biplastics are made by cladding and pressing molten sheets of thermosetting plastics on glass cloth and mats, followed by strengthening them with glass fiber materials with polyester binder. Tests of these biplastics in prototypes of chemical equipment showed the possibility of their use in equipment functioning with simultaneous exposure to corrosive media, temperature, and pressure (vacuum).

The longevity of articles made of glass-reinforced plastics can be enhanced by using hollow shaped fibers and microtape. By employing this kind of reinforcement, the weight of equipment can be significantly reduced and the stiffness and modulus of elasticity of the material are increased ( $7.0 \cdot 10^5$  as against  $2.0 - 3.0 \cdot 10^5$  kg/cm<sup>2</sup>). In addition, fabricating pipes and equipment by microtape winding significantly increases their gas-tightness.

A significant effect of enhancement of longevity and resistance of articles is achieved when polyester maleic resins of the PN-1 type are replaced with TMGF-11 and TGM-3 polyester acrylate resins [38], and also with diane type polyester resins (based on bisphenols).

Radiation methods of curing binders must be used to accelerate the production of articles from glass-reinforced plastics. This method enhances the physicomechanical indicators and long-term strength of glass-reinforced plastics and articles made therefrom.

## CHAPTER THREE

### METHODS OF TESTING REINFORCED PLASTICS

#### General Principles

In contrast to traditional structural materials, reinforced plastics exhibit specific properties that must be taken into account when conducting mechanical and other types of tests. Above all, these materials are practically nonreproducible if their fabrication technology, and conditions of conditioning, testing, and operation are not strictly regulated. Further, since reinforced plastics are heterogeneous materials, their properties will be governed by the properties of the individual components. The properties of reinforced plastics must correspond to the conditions of their use, i.e., they are determined by the nature of the ambient environment, temperature, nature of exposure to external loading, and the time during which the load is applied. A major disadvantage of existing standards for mechanical tests of plastics is that they take little account of these factors.

Reinforced plastics are characterized by anisotropy of mechanical properties, which places heavy emphasis on the requirements of determining all components of the strain and stress tensors [36, 39].

Standards for mechanical tests of plastics existing in the USSR and other countries are marked by great diversity. At times the same test method applies for reinforced plastics as for thermosetting plastics or molding compounds. The difference in the test methods leads to the impossibility of comparing results obtained in different laboratories and in different countries. This hampers the development of generalized engineering methods of calculation and the reliable evaluation of the bearing capacity of a structure.

The dependence of the mechanical characteristics of polymeric materials on time, nature of the ambient environment, load, and temperature make it necessary, when testing reinforced plastics, to model their service conditions. Short-term machine tests based on standards must serve only as a starting point for further comprehensive investigations of a material.

Compliance with requirements on the modeling of actual technological service regimes gives rise to the discrepancy between test methods and existing TU [Technical Regulations] and GOSTy [State Standards]. These tests afford reliable and dependable material for the calculation of structures. However, to obtain comparable data with this approach to the investigation of the properties of reinforced plastics and to achieve their scientific generalization, the following data are essential:

total characterization of the test materials -- type of material (composition, ratio of components, and lay-up scheme of reinforcement), fabricating regime, shape and dimensions of initial blank, and so on;

shape, dimensions, and fabrication method of specimens, conditions for the conditioning of specimens, mounting method, and number of specimens for the experiment.

characteristics of the test machine and measuring equipment, characteristics of the ambient environment, and temperature;

loading regimes -- the method of applying the load and the loading rate; and

method of interpreting the experimental data and confidence limits (error and scatter).

Generally, existing technical characteristics of reinforced plastics, as is true also for plastics, unfortunately contain a very limited amount of data useful to the designer from the standpoint of engineering calculations. The designer of chemical equipment and machines finds himself in a specially difficult position since data on the chemical resistance of materials is nearly totally unrelated to the characteristics of longevity, and the qualitative evaluation of the suitability of a material as, for example, the material is "quite resistant," "satisfactorily resistant," and so on, in combination with numerical values of the strength limits is far from adequate for the calculation of equipment.

To solve practical problems, as a rule one must independently determine the needed physicomechanical characteristics from the results of short-term and long-term static (in the simplest case) tests in specific operating conditions.

Methods of short-term static tests based on existing standards are quite fully described in the literature [23, 37, 60, 65].

In mass tests when it is required to select a large number of specimens, the constancy of their fabrication technology must be strictly observed, for example, reinforcing materials and binders must be selected from the same batch, the assigned orientation of fibers and the ratio of constituents, temperature-time molding regimes, and so on must be strictly observed. Emphasis must be given to providing test conditions in accordance with specific conditions simulating the service situation.

To obtain comparable results, test conditions must be standardized, i.e., the specimens must be conditioned. In general, in each specific case

the investigator, guided by scientific considerations and the specific capabilities of his laboratory, must specify the conditioning conditions.

Of the existing standards for the conditioning of specimens of plastics prior to testing, the most advanced is the ASTM standard (Method D-618-61). This standard proposes six typical conditions for the preparation of specimens in relation to temperature and humidity at which the tests are made. The conditions are governed by the temperature, humidity, and the time period during which the specimens are conditioned. According to this standard, the following parameters are specified for the ambient environment: temperature --  $23 \pm 2^\circ$  C (or  $\pm 1^\circ$  C), and relative humidity 50  $\pm 5$  percent (or  $\pm 2$  percent). These quantities are measured not farther than 600 mm from the specimen. The conditioning period is determined by specimen thickness; for example, the period is 40 hours for specimens not thicker than 7 mm.

It is particularly vital to standardize conditions in corrosion tests (GOST 12020-66). Below will be given representative methods for this type of testing. Here however it must be stated that as in the evaluation of chemical resistance from weight change and from the change in the mechanical strength, the weighing and failure of specimens must be carried out under strictly regulated conditions.

Without aiming at completeness of classification, existing methods of testing reinforced plastics that permit the determination of characteristics needed by the designer of chemical equipment can be divided into the following groups:

short-term static tests to determine strength and deformation characteristics (modulus of elasticity, ultimate strength, limit of proportionality, maximum deformations, and Poisson's ratio);

short-term dynamic tests (dynamic modulus of elasticity and the dependence of ultimate strength on deformation rate);

long-term static tests (dependence of strength on the loading time -- longevity and deformability -- and the plotting of creep curves); long-term static tests must also be organized with combined exposure to temperature and corrosive medium;

long-term dynamic tests (fatigue strength for cycles numbering  $10^5$ ,  $10^6$ , and  $10^7$ , and the determination of the logarithmic decrement of damping in bending);

corrosion tests in corrosive media with the plotting of the curve describing the dependence of weight change and change in strength characteristics with time; and

special tests (for example, the effect of bonded and unbonded abrasive on the properties of reinforced plastics, testing for permeability and gas-tightness, study of the effect of radioactive irradiation, and so on).

Many of these tests can be conducted on specimens of different types.

Flat specimens made of sheet material or else flat specimens specially molded by the heat-fabricating technology [64] are used in many laboratories.

In recent years tests of specimens of other types gained wide acceptance: rings, cylinders, and pipe segments.

Ring specimens are usually fabricated by winding filament impregnated with binder on a short cylindrical mandrel to obtain a relatively narrow and thin-walled circular specimen. In some cases ring specimens are cut from cylinders or from pipes.

Cylindrical specimens differ from ring specimens by their relatively greater length. In the winding of cylinders, reinforcing fibers are oriented in the most dissimilar fashion. Specimens in rod form are similarly fabricated.

In industry it is usually believed that flat and ring specimens can be used in building any new material or in investigating the effect of various factors on the properties of reinforced plastics.

There are different points of view as to whether tests on flat specimens afford the designer all the data he needs. Doubtless, cylindrical specimens, and especially tubular specimens, afford greater potentialities to gather calculated data needed by the designer of chemical equipment.

The anisotropy of properties made it necessary to conduct tests in even two mutually perpendicular directions ( $\phi = 0^\circ$  and  $\phi = 90^\circ$ ), and in the best of cases -- in three directions of specimen orientation ( $\phi = 0^\circ$ ,  $\phi = 90^\circ$ , and  $\phi = 45^\circ$ ). This is particularly important for testing with flat specimens.

In addition to these tests, builders of structures must organize, in their prototype production, tests on scale models and on experimental models in full size in service conditions in order to revise calculation data.

#### Short-Term Static Tests

Tension. Standards set various dimensions of flat specimens intended for tensile testing, however their shape as a rule is the same (Fig. 26). In tensile testing it is important that the working part be in a uniform stressed state. Specimens must be centered well in grips, ensuring strictly uniaxial stretching. Experience in the mechanical testing of laminated plastics with flat specimens showed that the standard shape of specimens is unsuccessful, since in most cases the rupture takes place at the site of the transition from the working part of the specimen to the thickened section.

In making tests with self-tightening wedge grips, lateral pressure on the specimen is increased when there is an increase in the tensile force.

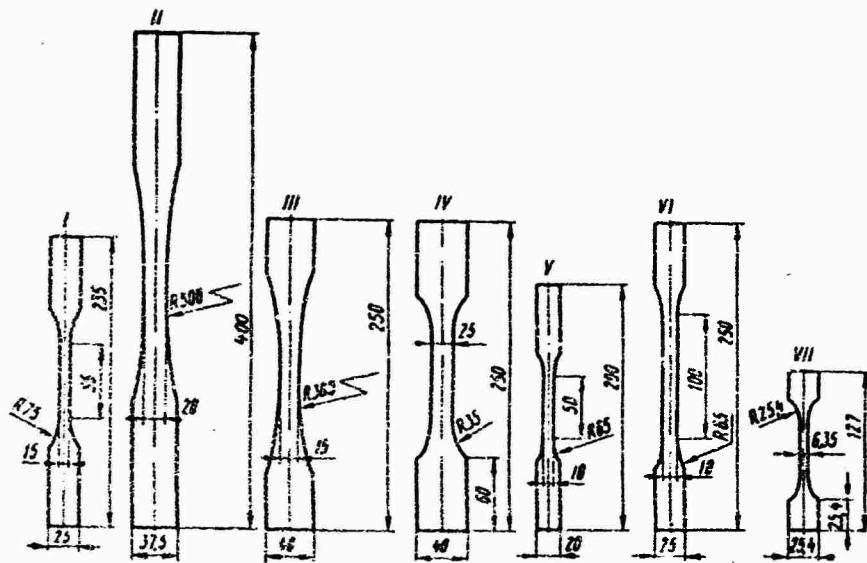


Fig. 26. Shape and dimensions of specimens for tensile testing of reinforced plastics:

- I -- based on GOST 4649-55
- II -- according to Ericson and Norris
- III -- short, according to Ericson and Norris
- IV -- elongated, based on DIN No 53455/1
- V -- based on DIN No 53455/1
- VI -- based on DIN No 53455/2
- VII -- based on Dietz and Mac Harry

This produces a high stress concentration leading to the rupture of specimens in the grip itself [40]. To eliminate this effect, several standards, for example, ASTM (Method D-638), recommend that specimen ends be additionally reinforced.

Most expedient are oblong specimens in the form of a straight bar [40] with strengthening at the grip locations. A grip used for clamping specimens by the force of friction is recommended for bar-shaped specimens. This method of securing specimens eliminates the possibility of their failure in the grip itself.

The dimensions of specimens must be such that uniform stresses ensure throughout the specimen length, accurate deformation reading is afforded, and the end effect can be neglected. When selecting the working part of the specimen and its support section, functions from the study [67] can be used.

There are also different views on the loading rate. The standard recommends grip travel rates in the range 10-20 mm/min. Some studies [79]

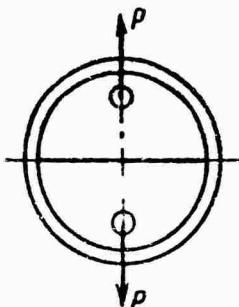


Fig. 27. Scheme for tensile testing of ring specimens

show that for more exact results the grip travel rate is best reduced to 6-15 mm/min.

Tensile tests are also conducted on ring and cylindrical specimens [57]. To apply the tensile load on a ring specimen, within it are inserted two steel semicircular grips and the load is imposed as shown in Fig. 27. Surfaces in contact are lubricated to reduce losses due to friction.

Ring specimens can be tested for tension in different ways. Sometimes a notch is made on the internal surface of the specimen to preclude bending and to ensure that the specimen fails along the notch. The width of this type of specimen is 25.4 mm. In another case, grooves are cut into semi-circular grips so as to leave a free section (51 mm) on the ring in which to place a strain gauge. The specimen diameters are 146, 228.6, and 152.4 mm for width of 6.4, 12.7, and 25.4 mm, respectively. The modulus of elasticity is calculated by the equation

$$E = \frac{P}{2bt\epsilon}, \quad (9)$$

where  $P$  is the load in kg;

$b$  is specimen width in cm;

$t$  is wall thickness in cm; and

$\epsilon$  is relative deformation within the elastic limit.

The method of hydrostatic testing of circular specimens for tension is of interest. This test method models the stress state of pipes and shells loaded with internal hydrostatic pressure. A specimen fails under the effect of radial tensile stresses. When tests are conducted by the hydrostatic method, a liner made of elastomer is placed within the ring (146 mm in diameter, 6.4 mm in height, and 3.2 mm in thickness) and the entire assembly is exposed to an increase in hydrostatic pressure until the moment of failure. Since the wall thickness of the ring is small, the specimen can be considered as a thin-walled specimen. To determine

the relative deformation  $\varepsilon$ , a string is wound over the outer surface of the specimen and the change in circumference is noted:

$$\varepsilon = \frac{\Delta l}{\pi D_{av}}, \quad (10)$$

where  $\Delta l$  is the elongation of the string; and  $D_{av}$  is the mean diameter of the circle.

When testing cylindrical specimens for tension, their ends are strengthened and they are given a conical shape. Tension is calculated by the formula

$$\sigma = \frac{4P}{\pi (D_0^2 - d_i^2)}, \quad (11)$$

where  $D_0$  and  $d_i$  are the outer and internal diameters in cm.

Compression. In compression tests, the shape and dimensions of specimens have an even greater effect on test results and on the function  $\sigma_{com} = f(\varepsilon)$  [96]. GOST 4651-68 recommends specimens in the form of an oblong prism 15 mm in height and with a 10 x 10 mm base. Comparative tests of specimens with different dimensional ratios showed the inadvisability of using shallow specimens [65]. An inflection appears on the plot  $\sigma_{com} = f(\varepsilon)$  for the specimens owing to the confinement of the deformation. Values of ultimate strength and the modulus of elasticity proved to be understated.

The ASTM standard (Method D-695) allows the ends of a specimen to be reinforced in order to prevent crushing.

Compression tests in certain laboratories are conducted on ring specimens [30, 100], and here various methods are used. Fig. 28 shows one such test method, where

$$\sigma = \frac{P}{2bl}. \quad (12)$$

Fig. 29 shows another test method. Under this loading scheme the modulus of elasticity in compression is calculated by the formula

$$E_{com} = \frac{1,786 r_{av}^3}{bl^3} \cdot \frac{P}{f}, \quad (13)$$

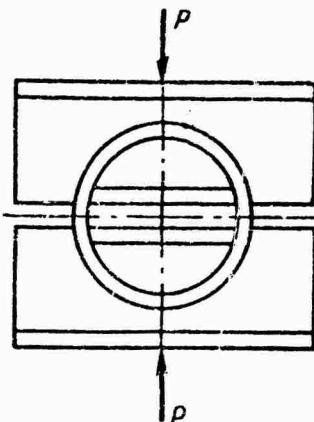


Fig. 28. Scheme for compression testing of ring specimens

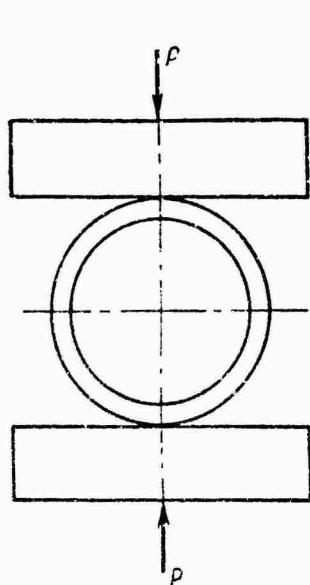


Fig. 29. Scheme for testing ring specimens for compression with bending

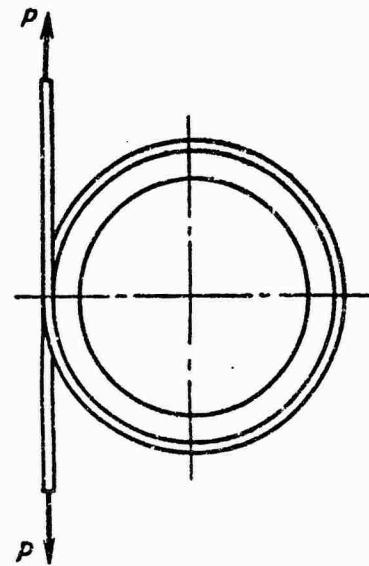


Fig. 30. Scheme for testing ring specimens by squeezing with a flexible tape

where  $E_{\text{com}}$  is the modulus of elasticity in compression in  $\text{kg}/\text{cm}^2$ ;

$r_{\text{av}}$  is the mean radius in cm; and

$f$  is the overall sag (displacement of the head of the measuring instrument) in cm.

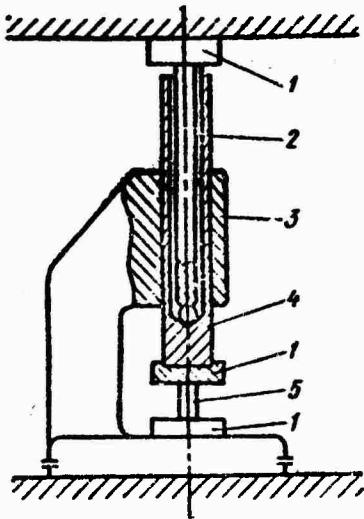


Fig. 31. Device for compression testing of specimens [83]:  
 1 -- support  
 2 -- prop  
 3 -- frame  
 4 -- plunger  
 5 -- specimen

Fig. 30 presents a compression test method that involves squeezing a ring with a flexible band. By this method, a steel band is wrapped around the ring and one end of the band is passed into a slip provided in the other end of the band, by which the total encirclement of the ring is achieved. The load is applied at the ends of the band. By this method the ring is subject to uniform compression. Surfaces in contact are lubricated, and a spacer placed at the conjunction of the band ends in order to eliminate bending at this point. The ultimate strength is calculated by the formula

$$\sigma = \frac{P}{t}. \quad (14)$$

Tests of ring specimens can be conducted by the hydrostatic pressure method. For this purpose, a special gasket ring made of elastomer is fitted over the circular specimen, and the hydrostatic pressure is applied to this elastomer ring. The ring specimen thus is subject to a uniformly compressing load.

In compression tests special emphasis must be given to the method by which the load is applied. It must be applied across plane-parallel surfaces. Special devices have been designed for this purpose, one of which is shown in Fig. 31.

bending. Bending tests are the most widespread owing to their simplicity of execution. However, this kind of test gives results that are hard to compare and the results can be used only for a qualitative evaluation. Results of testing laminated plastics for bending are interpreted based on the formulas from the strength of materials that do not allow for the anisotropy of the mechanical properties of materials [65].

According to the GOSTy [State Standards] and many foreign standards, tests for transverse bending are conducted on specimens in the form of oblong parallelepipeds with loading following the scheme of a beam resting freely on two supports. Here the loading must be applied either with the force placed in the middle, or else by the pure bending scheme.

When making tests for transverse bending, sag is measured as a function of the applied load and the rupture force. It must be noted that these tests do not allow for the effect of tangential stresses during bending. To estimate the error introduced, it is proposed to use the formula of S. P. Timoshenko [65].

Investigations [67] showed that the sag of a beam loaded with a concentrated force in the middle of its span is associated with the applied force by the function

$$f = f^*S \quad (15)$$

where  $f^* = (1/48) \cdot (P l^3 / E_{xx} J_x)$  is the sag calculated with shear disregarded; and

$S = (\kappa/3) \cdot (th \kappa / (\kappa - bh \kappa)) + \pi^2/8$  is the corrective factor that allows for the effect of shear.

The parameter is

$$x = \pi \frac{H}{l} \sqrt{\frac{E_{xx}}{G_{xz}}}.$$

In these expressions we have the following notation:

$J_x$  is the moment of inertia of the cross-section of the beam;

$E_{xx}$  is the modulus of elasticity;

$G_{xz}$  is the modulus of shear;

$l$  is the span of the beam;

$P$  is the applied load;

$H$  is half the beam height;

$h$  is the beam height; and

$b$  is the beam width.

The ratio  $E_{xx}/G_{xz}$ , depending on the material, lies within the limits 7-20.

Tests based on the pure bending scheme make it possible to determine the modulus of elasticity quite accurately.

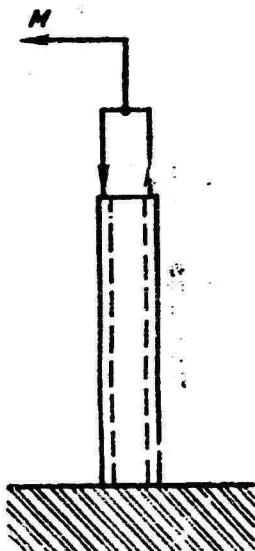


Fig. 32. Scheme for testing tubular specimens for bending

In making tests for transverse bending, special attention must be given to the execution of supports and the endpiece of the test machine. They must be made in the form of cylindrical surfaces with a radius of curvature of  $3H$  (but not less than 3 mm).

The literature contains general information on tests of laminated plastics for longitudinal sag. Thus, the critical stress  $\sigma_{cr}$  when cylinders are tested for longitudinal sag can be calculated by the formula

$$\sigma_{cr} = \frac{E}{\sqrt{3} \sqrt{1 - \mu^2}} \cdot \frac{t}{r_{av}}, \quad (16)$$

where  $\sigma_{cr}$  is the critical stress at which longitudinal sag takes place;  $l$  is the distance between grips;  $\mu$  is Poisson's ratio; and  $r_{av}$  is the mean radius of cylinder.

Equation (16) is theoretical and was derived for thin cylindrical pipes. However, it was noted that longitudinal sag usually occurs at stresses considerably smaller than this theoretical value  $\sigma_{cr}$ , as a result of defects, load eccentricity, and so on.

Also described [57] are tests of a cantilever-mounted cylinder with a force couple applied by means of levers (Fig. 32).

Specimen geometry and the ratio of cylinder radius to cylinder thickness are chosen so that failure takes place due to longitudinal sag. The critical stress is calculated by the formula

$$\sigma_{cr} = \frac{M r_{ex}}{J}, \quad (17)$$

where  $M$  is the bending moment;  
 $r_0$  is the outer radius; and  
 $J$  is the moment of inertia.

In the general case,  $J = (\pi/64) (R^4 - d^4)$ , and for very thin rings  $J = \pi r_{out}^3$  (where  $D$  and  $d$  are the outer and internal diameters).

The bending moment is

$$M = \frac{E}{12(1-\mu^2)} r_{ex} l^3. \quad (18)$$

**Shearing and crumpling.** These types of tests are conducted to estimate the behavior of reinforced plastics in unions. Below are presented several methods followed from foreign practice.

Tests for "interlaminar" shearing (Fig. 33) are conducted on analogy with tests for bending with the loading imposed in the middle, but the distance between the supports is chosen to be small so as to cause failure as the result of horizontal ("interlaminar") shearing. The ultimate shear strength is

$$\sigma_{av} = \frac{3P}{4bh}, \quad (19)$$

where  $P$  is the rupture load;  
 $b$  is the width of specimen, 25.4 mm; and  
 $h$  is the height of the specimen, 3.2 mm.

The specimen length  $l$  is 25.4 mm.

Tests for shearing of a ring specimen are conducted according to the scheme shown in Fig. 34.

The ultimate shear strength is

$$\sigma_{av} = \frac{P}{\pi D_r h}, \quad (20)$$

where  $D_r$  is the diameter of a sheared ring.

Crumpling tests are very simple: a metal pin (peg) is inserted into a calibrated opening of the specimen, and to the pin is applied along the

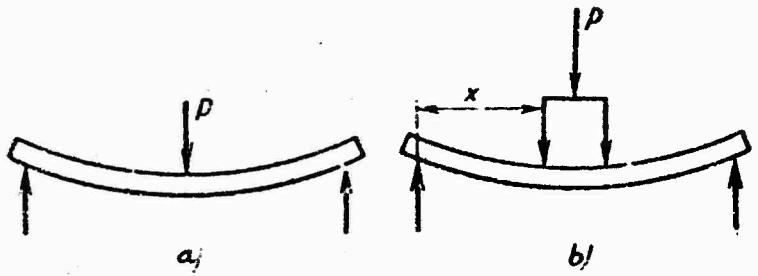


Fig. 33. Scheme for testing specimens for interlaminar shearing using loading with a concentrated force (a) and loading based on the net-bending scheme with  $x < l$  (b)

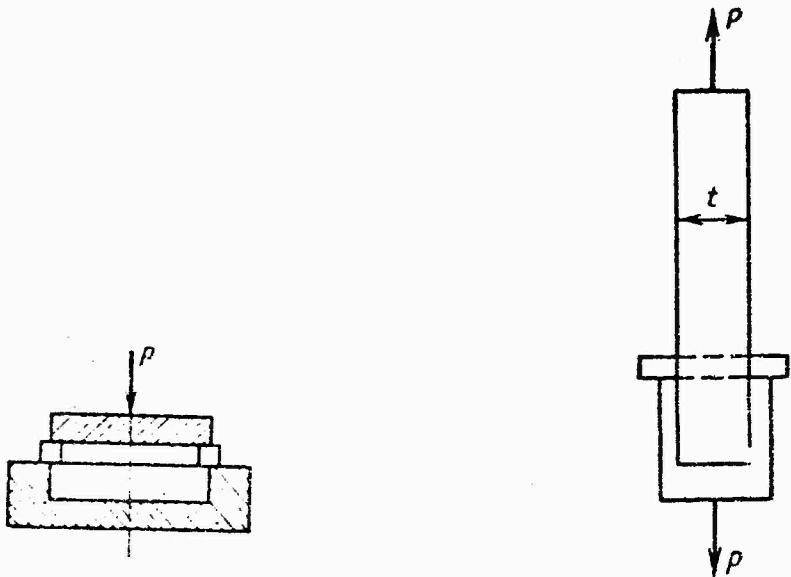


Fig. 34. Scheme for shear testing of a ring specimen

Fig. 35. Scheme for testing specimens for crumpling

longitudinal axis of the specimen the tensile or compressive load and the deformation of the opening in the test material is measured (the displacement of the pin). Fig. 35 presents the scheme for testing specimens for crumpling according to ASTM (Method D-953-54).

The following are determined according to the data obtained:  
crumpling stress

$$\sigma_{ind} = \frac{P}{dt}; \quad (21)$$

The tangential elastic modulus for  $\epsilon = 4.0$  percent is

$$E_t = \frac{\sigma_{td}}{\epsilon_{td}} = 250 \text{ N/mm}^2 \quad (22)$$

where d is the opening diameter.

The diversity of pipe designs, the use of more and more new kinds of resins for binders, the advancement in production methods, and the improvement in the technology of fabricating pipes from glass-reinforced plastics often makes it inadvisable to conduct expensive studies to determine their physicomechanical properties. For this purpose one needs a reliable relative criterion to estimate chemical resistance and other properties of pipe material. This criterion must take into account not only differences in the design of individual layers of the pipe wall, but also is sensitive to change in physicomechanical properties of piping after unilateral exposure to corrosive media and other external factors, for example, temperature, load, and so on.

Stiffness ( $EJ$ ) of ring specimens [19, 91, 96] cut from piping is this criterion, where E is the modulus of elasticity in bending and J is the moment of inertia of the ring cross-section.

Ring specimens (0.1 D in width) are subject to stepwise loading with two tensile or compressive forces P ranging from 1 to 5 kg (cf. Fig. 29). The function  $P - \Delta D$  is plotted from the resulting values of deformation and the forces corresponding to them, where  $\Delta D$  is the deformation of the ring specimen in the diametral direction. When tests are conducted on a rupture machine, this function is plotted automatically by a recorder. During testing, each ring specimen is loaded three times, and each subsequent loading is made after the ring specimen has been rotated by an angle of  $60^\circ$ . The mean value of deformations reflects the effect of flaws and cracks in the pipe wall, and also variation in wall thickness and physicomechanical properties of wall material with exposure to a corrosive medium.

Based on the resulting function  $P - \Delta D$ , a calculation is made of the stiffness of ring specimens that reflect the condition of the pipe material after certain periods of service in corrosive media. The slope  $\alpha$  of the function  $P - \Delta D$  is proportional to the stiffness of ring specimens [20, 36].

The deformation of a ring specimen diametrically is expressed in the form

$$\Delta D = \frac{P}{EJ} 0.149 r^3,$$

from whence we get the stiffness of the ring specimen

$$EJ = 0.149 r^3 \frac{P}{\Delta D}. \quad (23)$$

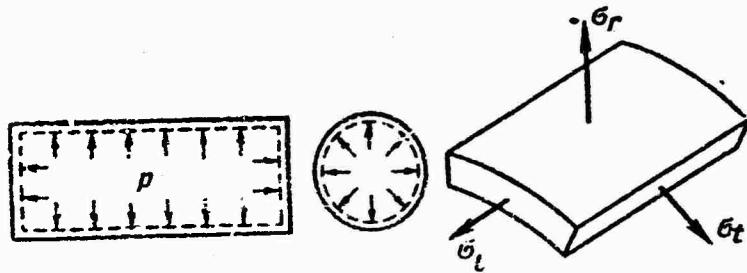


Fig. 36. Scheme for loading specimens with internal hydrostatic pressure

Hydrostatic tests of cylinders (pipes). In many laboratories in the USSR and abroad tests are made with internal hydrostatic pressure using wound structures of reinforced plastics: vessels, tanks, pipes, and so on. These tests include the following:

verification tests in which the capability of a given structure to withstand a specified internal hydrostatic pressure is determined;

rupture tests in which the specimen is brought to failure (in these tests used mainly to estimate the suitability of a material and structure, the pressure at which failure takes place is vital, and the stresses induced in the structure are not determined precisely);

tests on models to obtain calculation data that can be conducted with models of different sizes, all the way to full size (during such tests a large amount of data is obtained on the relationship between stress and strains, creep, fatigue, and so on); and

tests to determine the characteristics of the material (this kind of test is the most widespread).

Tests using external pressure on cylindrical (tubular) specimens are conducted to a much smaller extent than tests using internal pressure.

Testing with internal hydrostatic pressure is the most widespread. In the general case when the vessel is subject to internal hydrostatic pressure (Fig. 36), a triaxial stressed state is induced in a wall element, whose main components are as follows:  $\sigma_t$  is the normal stress in the tangential direction;  $\sigma_l$  is the normal stress in the longitudinal direction; and  $\sigma_r$  is the normal stress in the radial direction. For a thin-walled cylindrical specimen (wall thickness  $t < (1/10)r$ , where  $r$  is the radius) the normal stresses in the radial direction can be neglected, but the normal stresses in the tangential and the longitudinal directions are regarded as uniformly distributed. Usually tests with internal hydrostatic pressure are conducted on thin-walled specimens. These assumptions are not applicable to thick-walled cylindrical specimens.

In the ASTM, a method of testing pipes made of reinforced plastics using internal hydrostatic pressure has been standardized. In these tests specimens are placed in a water bath where they are thermostatted. The specimens are connected with a pressure source. The pipe system and the pretest specimens are filled with water or another liquid and hermetically closed. The pressure in the specimens is slowly increased until they fail. Specimen failure is not permitted sooner than 1 minute after the beginning of the tests. The strength is calculated by the formula

$$\sigma = \frac{p(D-t)}{2t}, \quad (24)$$

where  $p$  is internal pressure;

$D$  is the outer diameter of the pipe; and

$t$  is the wall thickness.

The working length of the specimen between the gaskets at their ends (1) must not be less than  $7D$ . When this requirement cannot be satisfied, the minimum free length of the specimen with outer diameter of 150 mm must not be less than 300 mm. For pipe width  $D > 150$  mm, when it is impossible to comply with the condition  $l > 7D$ , the free length of specimens is set by the tester [83].

Deformation can be determined using electrical resistance strain gauges cemented to the specimen wall. These strain gauges are sensitive to axial as well as transverse deformations. The resulting deformation can be used directly to determine the modulus of elasticity  $E$  ( $E = \sigma/\epsilon$ ) or with a correction to determine the biaxial deformation:

$$\epsilon_t = \epsilon_{t_0} + \mu_t \epsilon_{t_0};$$

$$\epsilon_t = \epsilon_{t_0} + \mu_t \epsilon_{t_0},$$

where  $\epsilon_t$  and  $\epsilon_t$  are the corrected deformations;

$\epsilon_{t_0}$  and  $\epsilon_{t_0}$  are the measured deformations;

$\mu_t$  is Poisson's ratio for material when the stress is applied in the axial direction; and

$\mu_t$  is Poisson's ratio for material when the stress is applied in the transverse direction.

Let us consider several other kinds of tests of tubular specimens described in the literature.

Transverse tension with internal pressure. For this type of test (Fig. 37), a cylindrical specimen with open ends is closed with plugs and brought to failure using internal hydrostatic pressure. The use of plugs prevents axial loading, so that only normal stresses in the tangential direction are set up. The end plugs can be used as pistons transmitting the pressure. For this purpose, the specimen is filled with silicone solution. Deformations can be determined using resistance strain gauges cemented to the outer surface of the pipe wall.

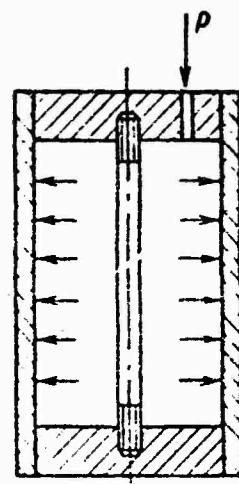


Fig. 37. Scheme for tensile testing of tubular specimens using internal hydrostatic pressure

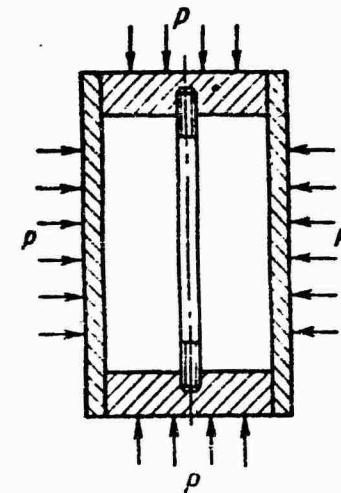


Fig. 38. Scheme for testing tubular specimens using external hydrostatic pressure

Testing using external pressure (Fig. 38). In this method of testing thin-walled pipes the external burst pressure is

$$p' = \frac{t}{r_{av}} \left[ \frac{\sigma_T}{1 + 4 \frac{\sigma_T}{E} \left( \frac{r_{av}}{t} \right)^2} \right], \quad (25)$$

where  $t$  is the wall thickness;  
 $\sigma_T$  is the slow limit of the material in compression;  
 $r_{av}$  is the mean radius; and  
 $E$  is the modulus of elasticity.

This equation is valid given the condition that  $p' r_{av} / t > \sigma_T$ .

The following equations are recommended for the determination of stresses in thick-walled cylindrical specimens [57]:

the uniform internal radial pressure (longitudinal pressure is equal to zero or is equalized by the external pressure)

$$\sigma_t = p \frac{\frac{r_{av}^2 + r_{in}^2}{r_{av}^2 - r_{in}^2}}{2}; \quad (26)$$

uniform external radial pressure (the longitudinal pressure is equal to zero)

$$\sigma_t = p \frac{2r_{ou}^2}{r_{ou}^2 - r_{in}^2}; \quad (27)$$

the uniform internal pressure in all directions

and

$$\sigma_t = p \frac{r_{in}^2}{r_{ou}^2 - r_{in}^2}$$

$$\sigma_t = p \frac{r_{ou}^2 + r_{in}^2}{r_{ou}^2 - r_{in}^2}; \quad (28)$$

uniform external pressure in all directions

$$\sigma_t = p \frac{r_{in}^2}{r_{ou}^2 - r_{in}^2} \quad (29)$$

and

$$\sigma_t = p \frac{2r_{ou}^2}{r_{ou}^2 - r_{in}^2}. \quad (30)$$

In equations (26) - (30),  $\sigma_t$  and  $\sigma_l$  are the normal stresses in the tangential and longitudinal directions at the internal surface,  $p$  is pressure, and  $r_{ou}$  and  $r_{in}$  are the outer and internal radii.

Thick-walled cylindrical specimens of the following dimensions were tested:  $D_{ou} = 81$  mm;  $t = 4.3-7.9$  mm; and  $h = 76.2 - 228.6$  mm.

#### Long-term Tests of Reinforced Plastics

Short-term static tests of polymeric materials, even though providing quite full characterization of their physicomechanical properties, still are not exhaustive for an evaluation of the bearing capacity of a material. As already indicated, the strength of reinforced plastics is strongly time-dependent. Therefore to determine rheological characteristics and to estimate the bearing capacity of a material and design with reference to the loading time and the nature of the time dependence of strength, long-term static tests must be made.

In addition, with reference to the specific details of the function of chemical equipment and pipelines, one must have information on the behavior of the material when exposed to an ambient corrosive medium and elevated temperatures. This information can be obtained only by making

long-term corrosion tests. Long-term tests of plastics are conducted in several directions. Most often these are either "traditional" corrosion tests with reference to temperature exposure, or tests for longevity without allowing for the effect of a corrosive medium. At the present time there is relatively little information on tests for longevity with reference to loading, corrosive medium, and temperature. It must be noted that the need to obtain these data led to expanding experiments on static fatigue of plastics in corrosive media.

In recent years considerable improvements have been introduced into the methods and techniques of corrosion tests, bringing them close to actual conditions of the service of articles.

Corrosion tests. In most cases, chemical resistance of components is determined to the first approximation, as is the resistance of the reinforced plastic in corrosive media. However, it must be borne in mind that the chemical resistance of reinforced plastics is sometimes decisively affected also by other factors that depend on the technology of fabricating the material, processing of the components, nature of the material, and so on. For example, if we consider the chemical resistance of components included in the composition of a textolite, we can establish that the reinforcing cotton or silk fabric is resistant, in particular, only to highly dilute solutions of acids. From this we can conclude that textolite is unresistant in acids. However, if as a result of technological processing of the material we ensure that the fibers are adequately protected with polymeric binder, textolite can become quite acid-resistant.

Another example. We know that furan resins are resistant to caustic alkalis, however in several studies [94] data are given on the unsatisfactory resistance of furan glass-reinforced plastics in sodium hydroxide. This can be explained only by the fact that the alkali acted on the glass fiber. Obviously, in selecting a glass fiber resistant to sodium hydroxide, the overall evaluation of the chemical resistance of the glass-reinforced plastic should be higher.

Therefore, in making a corrosion evaluation of a material, especially when developing some composition, an evaluation must be obtained of the corrosion resistance of the material itself, as well as its individual components. This permits introducing appropriate corrections into the composition and the technology of obtaining the material and fabricating the article.

The simplest method of corrosion testing is testing for water absorption according to GOST 4650-65. Tests are conducted in distilled water at normal temperature. Specimens with the dimensions  $(120 \pm 2) \times (15 \pm 0.5) \times (10 \pm 0.5)$  mm, after conditioning at constant humidity and temperature, are weighed, and then are loaded into distilled water for 24 hours. Then the weight change of the specimen is determined. These tests can also be conducted in other liquid media.

The chemical resistance of plastics to chemical reagents is estimated from the relative change in the averaged mechanical properties and the weight change (GOST 12020-66).

Reinforced plastics are mostly classified in the group of reaction plastics.

It must be noted that the estimation of the chemical resistance of plastics based on weight change is mechanically taken from the corrosion tests of metals. As a rule, it is not a reliable characteristic, especially when the weight change is measured over some fixed time interval. Different processes develop in various polymeric materials when they are in contact with a medium. Some swell, absorbing moisture, while in others components dissolve, while in still others structuration accompanied by weight change takes place on exposure to the medium, and so on. Most often many processes alternate in the same material. For example, in a study of polyester glass-reinforced plastic in diethyl phthalate after exposure of specimens for 623 hours, their weight increased only by 0.02 percent. Based on this experiment one could suggest the high chemical resistance of this material in diethyl phthalate. Actually, the pattern of weight change is as follows: the weight dropped by 0.06 percent in the first 50 hours, then rose by 0.07 percent, but at the end of the tests (in 623 hours) the weight increase was 0.02 percent. If the weight change curve is extrapolated, the increase in weight in one year will be 2.2 percent.

Thus, in estimating the chemical resistance of plastics by weight change, it is more correct to trace the kinetics of weight change over certain time intervals. As shown by numerous experiments, these investigations must be conducted on the basis of not less than 30 days (720 hours). An abrupt variation in the properties of the materials is observed in the first 200 hours of their contact with the medium (Fig. 39), but stabilization of the process takes place for a base of 200-600 hours. In this case it becomes possible to extrapolate to longer time intervals and to predict the behavior of the material. We must, however, note that when possible one must avoid purely gravimetric methods of estimating chemical resistance and adopt as the criterion of the chemical resistance variation in mechanical properties, for example, ultimate strength in tension, bending, or compression. In the above presented example with polyester glass-reinforced plastic in diethyl phthalate, the bending strength at 623 hours of exposure fell by 67 percent and, therefore, the material is unsuitable in these conditions. Additionally, one can trace the weight change by establishing when possible a relationship between the change in strength and in weight.

In most corrosion tests of plastics, it is precisely this method that is employed at present time. And in this case one must study the kinetics of the process for a base of not less than 30 days. Tests are usually conducted in Erlenmeyer flasks or in other vessels fitted with a reflux condenser. The corrosive medium is poured into the flasks, and the flasks themselves are thermostatted in a water, glycerin, or oil bath. After certain time intervals (10, 20, 30, and 40 days), some of these specimens

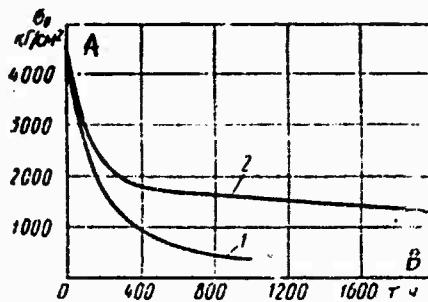


Fig. 39. Dependence of ultimate tensile strength on time for glass-reinforced textolite based on EF-32-301 resin after exposure in sodium hydroxide at 50° C:

- 1 -- 1 % NaOH solution
- 2 -- 20 % NaOH solution

KEY: A --  $\sigma_f$ , kg/cm<sup>2</sup>  
B --  $\tau$ , hours

are removed, their weight change is recorded, and then they are brought to failure. The results of tests are shown graphically in the coordinates  $\tau - \Delta G$  and  $\tau - \Delta \sigma$ , where  $\tau$  is time, and  $\Delta G$  and  $\Delta \sigma$  are the change in weight and in strength, respectively. If the change in strength and weight progresses with time, the material becomes unsuitable for the given conditions. If the weight, strength, and relative elongation vary only in the first test period, and thereafter the change process stabilizes, the suitability of the material is estimated by the values of these changes by extrapolation to desired service times. Use can be made of a scale for estimating the suitability of glass-reinforced plastics based on polyester and epoxy resins using weight change (Table 20). The weight change in a year is determined by extrapolating results obtained for a base of 200-600 hours of testing.

Assumptions are made as to the presence of a correlation between weight change (extrapolation for a year) and strength change. However, this correlation appears doubtful in general form and has been refuted by several experimenters [98].

In conducting corrosion tests of plastics, one must ensure constant composition of the corrosive medium (pH monitoring) and replenishment of the medium during the test period. The medium must be stirred to obtain more or complete results.

A weighty methodological problem is the question of selecting the failure time of specimens after conducting the tests. There is no single point of view here. It appears to us that the failure of specimens

TABLE 20. SCALE FOR ESTIMATING THE CHEMICAL RESISTANCE OF PLASTICS

<sup>1</sup> Изменение веса за год (экстраполяция по 600 ч испытаний) в %	<sup>2</sup> Оценка химической стойкости	<sup>3</sup> Примечания
-0,25+ +0,25	Отличная <sup>4</sup>	-
$\pm 0,25 \pm 0,75$	Хорошая <sup>5</sup>	-
$\pm 0,75 \pm 1,5$	Удовлетворительная <sup>6</sup>	<sup>9</sup> Имеется опасность расслоения; для оценки пригодности требуются более длительные испытания
<sup>7</sup> Свыше $\pm 1,5$	Плохая <sup>8</sup>	<sup>10</sup> Материал непригоден

- KEY:
- 1 -- Weight change in one year (extrapolation from 600 hours of testing) in %
  - 2 -- Estimation of chemical resistance
  - 3 -- Remarks
  - 4 -- Excellent
  - 5 -- Good
  - 6 -- Satisfactory
  - 7 -- About  $\pm 1.5$
  - 8 -- Poor
  - 9 -- There is a danger of exfoliation; longer tests are required to estimate suitability
  - 10 -- Material is unsuitable

must be achieved when their weight reaches a constant value upon drying in atmospheric conditions at 18-20° C and a relative humidity of 65 percent. (The drying conditions may differ, but they are always constant.)

In corrosion tests using flange specimens, much difficulty is represented by the protection of end surfaces against the penetration of the medium. Usually the ends of specimens are protected with the same binder as used in the material, or with an epoxy compound. Good results can be obtained if specimens are cut from an uncured stack using a special punch, and then the finished specimens are cured. In this case it is possible to protect the ends with binder [64].

Of considerable interest are stand corrosion tests of pipes made of reinforced plastics during which, in addition to the effect of the corrosive medium, allowance is made for hydrodynamic conditions of the surface of pipes and equipment.

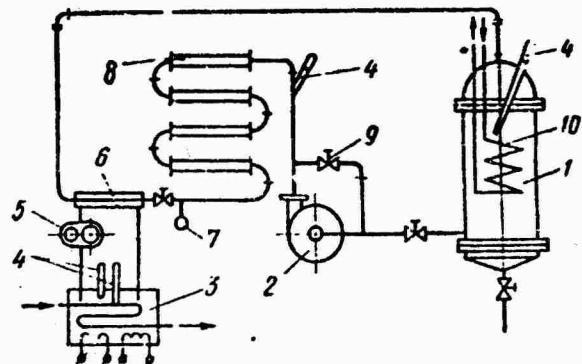


Fig. 40. Scheme of a device for testing tubing for chemical resistance in a flow of corrosive media

- 1 — tank
- 2 — centrifugal pump
- 3 — heater
- 4 — thermometers
- 5 — oil pump
- 6 — heat exchanger
- 7 — manometer
- 8 — pipe specimens
- 9 — by-pass valve
- 10 — coils

Fig. 40 shows a layout of such a stand. After certain time intervals, circular specimens are cut from the pipes and subject to machine tests based on procedures described in the preceding sections. The change in physicomechanical characteristics of the material is determined. By varying the rate at which the medium flows, producing different local drag values, one can trace the effect of hydrodynamic conditions on the chemical resistance and longevity of the pipes.

In conclusion, it must be noted that at the present time there is already available some material on the chemical resistance of reinforced plastics. However, information on chemical resistance sometimes is extremely contradictory, partly owing to differences in the formulation of the material and in its production procedures, and partially owing to differences in experimental conditions. The absence of information on methods of estimating chemical resistance poses considerable difficulties when analyzing and using literature data.

Long-term static tests. As already indicated, long-term static tests are conducted to determine the time dependence of strength and to determine rheological characteristics. As a rule, long-term static tests are conducted under conditions of creep with constant stress. These studies can be conducted in the atmosphere, as well as in media that are corrosion and surface-active at room and at elevated temperatures.

A mandatory requirement for the determination of rheological characteristics of strength is the possibility of quite accurately determining the stressed state at any moment of time. This requirement is most reliably satisfied by testing with uniaxial tension [65]. It is because thus far accurate enough rheological theories of bending, torsion, shear, and the loss of the stability of rods made of inhomogeneous anisotropic material have not been developed. The lack of sufficiently exact theoretical solution does not permit a proper interpretation and evaluation of its experimental results. For this reason, it is customary to take as the main kind of long-term static tests the testing of specimens in conditions of creep with uniaxial tension, though there are other original solutions, and these will be given appropriate treatment below.

When testing laminated plastics for longevity in chemically corrosive media under conditions of uniaxial tension, there is the possibility of most fully studying corrosion-absorption processes occurring in them. Under conditions of uniaxial tension the "Rebinder effect" shows up most intensively, while at the same time in bending or compression some microcracks close up, and their role in the failure process associated with the sorption of surfactants diminishes, and the failure mechanism of the material predominates by the redistribution of stresses. For this reason it is difficult to agree with the view that testing for bending most completely shows the effect of corrosive media on glass-reinforced plastics.

Tensile stress is imparted to a specimen either directly by means of suspended weights (Fig. 41 a) or using a lever or a system of levers (Fig. 41 b).

Long-term static tests are usually carried out with constant stress or constant loading. In the case of small deformation (to 10 percent), we can neglect the change in the cross-sectional area of the specimen, and then the two methods give practically identical results. In the case of large strains when the cross-sectional area of the specimen changes decidedly during deformation, to retain constancy of stress values special devices automatically varying the loading are called for [3, 26]. Installations with devices of this kind are quite complicated, therefore in long-term tests of materials with large strains experiments are often conducted under conditions of constant loading [12]. As for most reinforced plastics, they are characterized by small strains, and to ensure constancy of stress values during an experiment most special devices are required.

When building installations for long-term static testing under creep conditions with uniaxial tensile stress, special attention must be given to the centering of grips so as to prevent longitudinal bending from occurring.

In long-term static tests, several problems can be solved. First of all, we can determine the longevity of a material by bringing specimens to failure, and we can plot longevity curves. Secondly, in parallel with

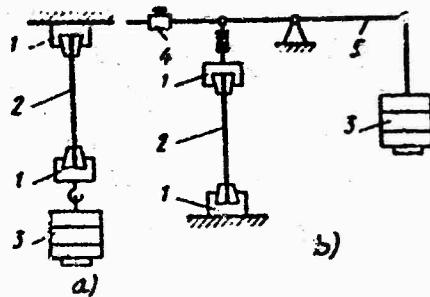


Fig. 41. Arrangements of devices for testing materials for longevity in creep conditions with direct loading of the specimen with weights (a) and loading using a lever system (b):

- 1 -- grips
- 2 -- specimen
- 3 -- weights
- 4 -- counterweight
- 5 -- lever

tests for longevity or separately, we can study creep with the determination from the creep curve of rheological characteristics. Deformation can be measured either using ohmic-resistance strain gauges, or else by means of various mechanical instruments, for example, Aristov strain gauges and clock-type indicators. When specimens are investigated in chemically corrosive media, indicators are most suitable, since they can be positioned outside the specimen directly on the grips which make it possible toward the necessity of protecting the measuring device against corrosion. When the indicator is secured on grips, the deformation of the specimen in the grips per se must be taken into account. Rheological characteristics can be determined by an accelerated method at elevated temperatures based on thermomechanical curves [65].

The third problem that can be solved consists in determining the effect of static loading on variation in mechanical strength. In this case specimens subject to constant loading are not brought to failure. After a certain time interval has elapsed the load is removed, and the specimens themselves are brought to failure on a rupture machine. The strength change is established. This method can be of interest from the standpoint of speeding up the plotting of longevity curves. Let us assume that a specimen is loaded with some tensile force that causes the stress  $\sigma_A$ . After certain time intervals ( $\tau_1$ ,  $\tau_2$ ,  $\tau_3$ ,  $\tau_4$ , and so on), the load is removed and the specimen is brought to failure. Rupture stresses will be  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ ,  $\sigma_4$ , and so on, respectively. If we represent these results graphically,

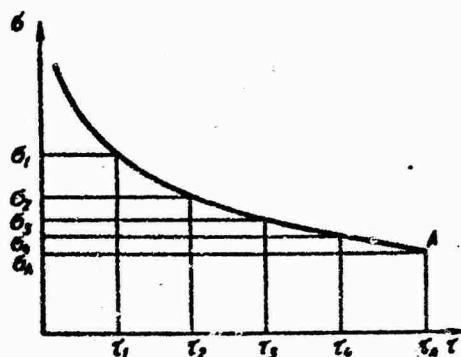


Fig. 42. Analytic-graphical method of determining the longevity of reinforced plastics

we will get a curve (Fig. 42) describing the dependence of the reduction in strength on time  $\sigma = f(\tau)$  at constant stress  $\sigma = \text{const} = \sigma_A$ .

Obviously, under the effect of the stress the specimen will fail when the curve reaches point A on a line parallel to the abscissa axis with ordinate  $\sigma_A$ . By determining the function  $\sigma = f(\tau)$  graphically or analytically, we can find the point A and, thus, the time  $\tau_A$  corresponding to it, which is equal to the longevity of the material. Of course, this method of longevity determination requires careful experimental verification, but by itself it opens up tempting possibilities for accumulating data, particularly on the longevity of materials in corrosive media at different concentrations and at different temperatures, since acquiring these data by the usual means is fraught with sizeable difficulties.

The longevity of reinforced plastics, in particular, glass-reinforced plastics, can also be determined by the Larson-Miller (Gol'dfeyn) parametric method.

Experiments showed that long-term strength R for glass-reinforced plastics in a small range of working stresses can be calculated by the formula

$$R = a - bp, \quad (31)$$

where a and b are constants of the material; and p is the Larson-Miller parameter.

For glass-reinforced plastics, we have

$$p = T(C + \lg \tau), \quad (32)$$

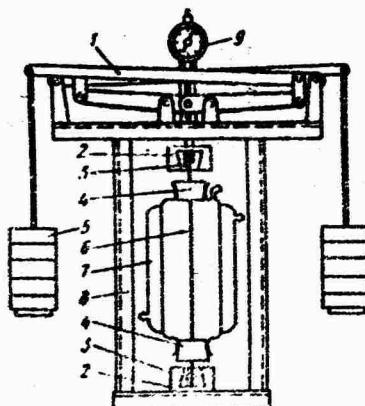


Fig. 43. Facility for testing reinforced plastics for longevity in tension:

- 1 — system of levers
- 2 — grip collars
- 3 — riffled jaws
- 4 — rubber plug
- 5 — set of weights
- 6 — specimen
- 7 — special glass vessel for thermostating corrosive medium
- 8 — frame
- 9 — clock-type indicator

where  $T$  is the test temperature in  $^{\circ}$  K;  
 $C$  is a constant ( $C = 20$  for glass-reinforced plastics, according to Gol'dfeyn); and  
 $\tau$  is longevity.

In determining long-term strength, use can be made of short-term tests at elevated temperatures, by plotting parametric curves [87].

In the literature a description is given of several different devices that can be used in testing reinforced plastics under creep conditions, however they all have appreciable drawbacks associated either with the impossibility of conducting the experiments in chemically corrosive liquids, or the limited temperature range, use of nonstandard specimens, and the like. Taking these disadvantages into account and the need to conduct mass testing of specimens, one of the authors proposed a simple device (Fig. 43). This device enables us to test an unlimited number of specimens (numbers of the devices can be brought together in an installation with a different number of cells) in various media: the atmosphere, water,

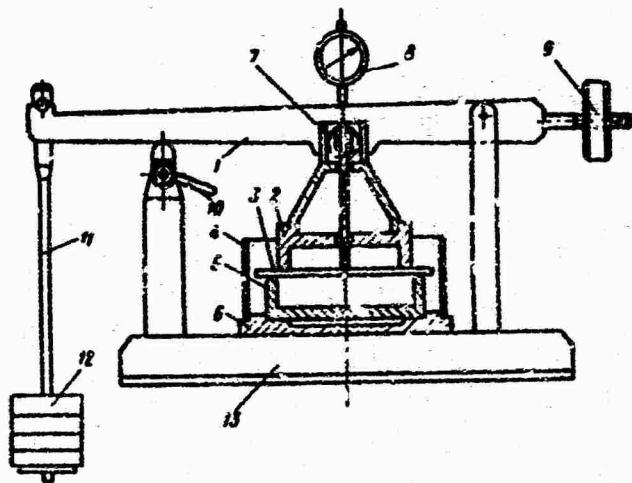


Fig. 44. Facility for testing reinforced plastics for longevity with bending:

- 1 -- lever
- 2 -- punch
- 3 -- specimen
- 4 -- vessel containing corrosive medium
- 5 -- support
- 6 -- vessel bottom
- 7 -- punch axis
- 8 -- strain gauge (clock type indicator)
- 9 -- counterweight
- 10 -- arrester
- 11 -- pole rod
- 12 -- set of weights
- 13 -- foundation

acids, alkalis, and so on at any temperatures (up to the boiling point of the liquid). The design of the device, the method of mounting and sealing the specimen in the vessel, and also these experimental techniques are given in detail in several reports [74, 75, 77].

The report [24] proposes a modification of this device with sliding bearings replaced with antifriction bearings in order to reduce frictional losses, and also with the recording of strain and the moment of specimen failure automated. However, as the result of replacing the system of two parallel-action levers with a single lever, considerable difficulties arose in centering the grips and in eliminating specimen sag.

A unit for studying long-term static strength in bending has an interesting solution [22] (Fig. 44).

Of high interest for practical purposes is obtaining data on the behavior in time of articles made of reinforced plastics in a complexly stressed state, which corresponds to actual service conditions. Analysis of the disadvantages of several devices for tests of this type led to the building of a more advanced unit [18] (Fig. 45).

#### Tests for Gas-tightness and Permeability. Determination of Diffusion Characteristics

Of decisive importance in the functioning of chemical equipment and pipelines often is not the total loss of strength and the failure of a material, but a breakdown in its fit, and the loss of the material's gas-tightness and permeability. To study these effects, we need to conduct special tests for gas-tightness and permeability. Methods are not standardized for making tests of this type. At the present time several methods of testing for permeability are employed.

The simplest test method was developed at the Department of Chemical Equipment Corrosion at the Moscow Institute of Chemical Equipment Building. Specimens in the form of disks 2-5 mm thick are tested by this method. Flat specimens are placed in special units (Fig. 46). Specimen 1 is pressed, by means of two rubber spacers 2, between two parts of a housing 3 that has two small cavities (A and B). The half-chambers are joined with bolts. The test liquid is poured into cavity A. Compressed nitrogen is fed through connecting piece 4. A pressure is built up in cavity A (usually 2-4 kg/cm<sup>2</sup>). The specimen is maintained in this condition for a definite time interval, but not less than 1 hour. The material is regarded as having passed the test if no traces of liquid are found on the surface that faces cavity B.

Among the disadvantages of this method are the following: the arbitrary choice of the test duration (even when it is strictly scientifically substantiated, it is difficult to estimate the permeability and gas-tightness of a material from a single point; the kinetics of the process must be studied), and also the impossibility of exactly fixing the moment of total passage of the liquid, since cavity B is closed to inspection.

This method can be recommended only for qualitative comparative tests. These disadvantages can be eliminated, and then the potentialities of the device will be much greater. First of all, it is necessary to make it possible to fix precisely the moment when the liquid penetrates through the specimen thickness. This can be done, for example, as follows. A foil must be cemented to the surface of the specimen facing cavity B, and two electrodes must be cemented to the opposite surface of the specimen. Then if an electrolyte is poured into cavity A, the moment of total permeability can be established from the appearance of electric current in the electrode circuit. The moment of total permeability can also be determined from the change in the electrical resistance of the foil and the glass-reinforced plastic.

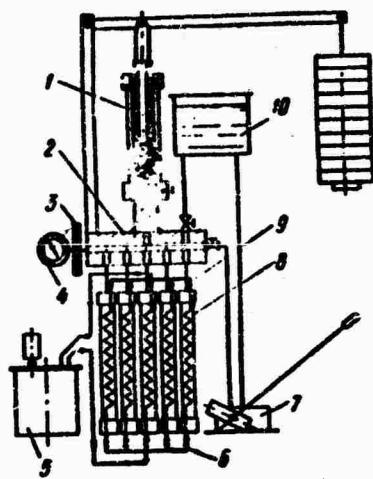


Fig. 45. Arrangement of stand for testing pipes made of reinforced plastics for longevity on exposure to hydrostatic pressure:

- 1 — weight device
- 2 — distributor
- 3 — separating chamber
- 4 — manometer
- 5 — thermostat
- 6 — collector for coolant supply
- 7 — hand pump
- 8 — specimen
- 9 — collector for coolant removal
- 10 — tank for liquid

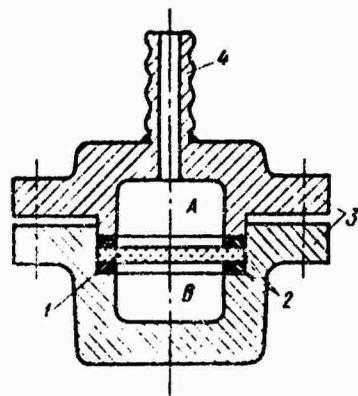


Fig. 46. Device for testing specimens for permeability

By solving this problem, more detailed studies can be made. It becomes possible to study longevity (in this case — time to total permeability of a specimen) as a function of the temperature of the medium (this requires thermostatting of the unit), pressure, nature of the medium, and its concentration. However, even in this case there is a disadvantage that is practically unavoidable when compressed gas tanks are used. In mass testing with devices of this type, several components are placed between the gas tank and the specimen: a gas reducer, receiver, throttle and check valves, distributor, and turnoff valves. In testing specimens, owing to their creep there is some enlargement of chamber A, which requires pressure to be regulated. There is also a drop in pressure due to some leakage of gas along the lines from the tank to the device. In installations of this type, the pressure drop is sometimes 5-10 percent in 24 hours. This requires manual regulation of pressure. In addition, the presence of a high-pressure gas tank increases the requirements on safety measures in conducting investigations.

These disadvantages of gas tanks are eliminated in the hydraulic stand for pipe testing (cf. Fig. 45). This facility also makes it possible to conduct tests of tubular specimens for tightness (gas-tightness). Constant pressure here is maintained by means of weight devices.

The disruption of gas-tightness occurs due to the initiation of porosity in piping walls. The presence of porosity leads to a drop in pressure and the appearance of "sweating" and drop effusion at the pipe surface. The loss of pipe gas-tightness in a certain time interval for given conditions (pressure, temperature, and concentration of a medium) can be estimated from these indications, i.e., we can estimate longevity. The moment of breakdown in gas-tightness can be fixed more exactly. Thus, the tube can be covered externally with foil and the variation in the electrical resistance can be recorded in the event that the wall proves to be permeable (Fig. 47). Good results can be achieved if a layer of indicator that changes color upon contact with a given medium is placed on the outer surface of the tubular specimen.

Recently serious attention has been given to studying the diffusion characteristics of polymers [13, 28, 46]. Diffusion processes strongly affect the aging of polymers and plastics based thereon. Variation in mechanical properties and also in the structure of a material depthwise is determined mainly by the rate at which the medium penetrates into the polymeric material. By knowing the diffusion rate, we can judge the permeability of a material and determine its service potentialities, i.e., essentially speaking, its longevity.

Diffusion is a process leading to the equalizing of concentrations within the same phase. When a liquid penetrates through a plastic, its molecules fill the molecular voids of the material, forming macromolecules owing to the continuous oscillatory movement of individual components. The medium can also penetrate through pores or thin capillaries. In this case diffusion is nonspecific and depends only slightly on temperature.

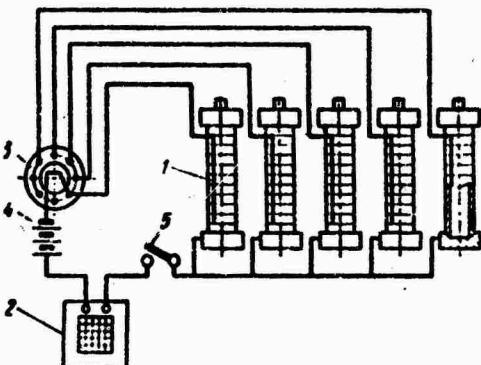


Fig. 47. Electrical block diagram for recording disruption of the gas-tightness of pipes made of glass-reinforced plastics:

- 1 -- specimen wrapped with aluminum foil tape
- 2 -- self-recording ampere-voltmeter
- 3 -- commutator mounted on clock mechanism
- 4 -- battery
- 5 -- electric switch

In most cases, polymeric materials are characterized by the first kind of penetration, i.e., activated diffusion, although penetration through pores and capillaries is also typical of composite plastics, which embraces reinforced plastics. The coefficient of diffusion is determined by the rate of sorption and has the dimension  $\text{cm}^2/\text{hr}$  or  $\text{cm}^2/\text{sec}$ . In addition, in studying diffusion characteristics one introduces the concept of the coefficient of permeability. The coefficient of permeability characterizes the passage of the vapor of the medium through a membrane 1 cm in thickness and 1  $\text{cm}^2$  in area for a pressure difference of 1 torr (1 mm Hg) per unit time at constant temperature. The coefficient of permeability has the dimension  $\text{g}/(\text{cm} \cdot \text{hr})$ .

Coefficients of diffusion and permeability are the main quantities characterizing the qualitative and quantitative aspects of the penetration of a medium into polymeric materials.

There are several methods of determining these coefficients [28]. Most widespread is the sorption method, which is based on the change in the mass of a specimen after exposure to a medium. The coefficient of diffusion here is determined by the formula

$$Q = Q_{\max} \left( 1 - e^{-\frac{4\pi^2 D \tau}{d^2}} \right). \quad (33)$$

where  $Q$  is the change in the mass of the specimen in grams, during the time  $\tau$ , in seconds, that it spends in the medium;  
 $Q_{\max}$  is the change in the mass of the specimen in grams on attainment of equilibrium;  
 $D$  is the coefficient of diffusion in  $\text{cm}^2/\text{sec}$ ; and  
 $d$  is specimen thickness in mm.

The sorption method found wide application in the determination of the water permeability of polymers, and also in the determination of the permeability of organic liquids. This method is inappropriate for the determination of the coefficient of diffusion of solutions of electrolytes, since the increment of the specimen in this case is an overall quantity and one cannot determine what is the cause of the weight change: penetration of the solvent or of a solute. In addition, in a great many cases, especially for concentrated acids, no swelling of the specimen is observed, since a breakdown of material due to chemical interaction takes place simultaneously with the diffusion of the medium.

The manometric method of determining the diffusion characteristics of polymers has gained wide acceptance [68], especially in studies conducted in gaseous media. The method is based on the fact that a specimen in the form of a thin film 30-100 microns thick separates the test media from the measuring chamber (cf. Fig. 46). The change in pressure is recorded in the measuring chamber when the diffusion characteristics of gases are determined, or the change in ion concentration and diffusion characteristics of electrolyte solutions are determined [78].

The coefficient of permeability  $P$  is calculated by the formula

$$P = \frac{Qd}{S\tau\Delta p}, \quad (34)$$

where  $Q$  is the amount of the substance in grams penetrating in the time  $\tau$ ;  
 $S$  is the surface of the specimen in  $\text{cm}^2$ ;  
 $d$  is specimen thickness in cm; and  
 $\Delta p$  is the pressure difference in torr between the volumes separated by the specimen.

The amount of gas or vapor  $Q$  is calculated by a formula derived from the Clapeyron equation:

$$Q = \frac{p'V\mu}{RT}, \quad (35)$$

where  $p'$  is the pressure produced by the vapor in the measuring chamber of the instrument, in  $\text{kg}/\text{cm}^2$ ;

$V$  is the volume of the measuring chamber in  $\text{cm}^3$ ;

$T$  is temperature in  $^\circ \text{K}$ ;

$R$  is the universal gas constant in  $\text{kcal}/(\text{kmole} \times \text{deg})$ ; and

$\mu$  is the molecular weight of the substance.

This material exhibits quite high accuracy, but requires complicated equipment. Its disadvantages include the fact that diffusion characteristics can be determined only for thin polymer films.

When the polymer is in contact with a liquid medium, the latter, on penetrating into the polymer, forms two regions with sharply distinct optical properties. Several methods of determining diffusion characteristics are based on this effect. To establish the interfaces of these regions, the interferometric micromethod is used [71].

Chemical methods are used for a more well-defined delineation of the boundary separating the "dry" polymer from the layer into which the medium has diffused.

In the literature [49] a description is given of methods of determining the depth to which solutions of various electrolytes have penetrated polymers, where indicators for the medium whose permeability is under study were used to reveal a well-defined penetration boundary. Indicators, on interacting with the ions of the medium penetrating into the polymer, abruptly change their color.

By measuring the depth of the colored layer, we can determine the depth  $x_0$  to which the diffusing medium has penetrated. The following formula derived on the basis of Ficke's law can be used with adequate accuracy in calculating the coefficient of diffusion  $D$  in this case:

$$D = \frac{x_0^2}{\pi t} \quad (36)$$

This method is quite simple and permits observation of the front of medium penetration and study of the kinetics of its penetration into many polymeric materials and plastics based thereon.

The conditions of indicator interaction with the medium can be satisfied in two ways. The indicator can be introduced directly into the test polymer (binder) as a finely-dispersed filler (colorant). In this case ions of the medium penetrating into the polymer interact with the indicator ions, and the zone in which this reaction takes place sharply changes its color. The depth of penetration is measured over sections 1.2-1.5 mm thick for plastic materials, or else on sections 2-3 mm thick for brittle materials. The indicator can be introduced into the polymer after the ions of the medium have diffused into it, where a section 20-15 microns thick is cut with a sledge microtome in the direction parallel to the

direction of diffusion is cut from a specimen exposed to the medium. Then the section is washed in distilled water and placed in a developer. The developer is a solution of the indicator in a liquid in which the polymer swells readily. After development, the section is removed from the developer, wiped with a pad soaked in acetone, and the depth of color change is determined.

As established in the paper [49], the concentration of the indicator in the developer can be arbitrary, but in concentrated solutions the section develops more rapidly and the penetration boundary is more clearly pronounced.

The 50-power MBI-3 biological microscope can be used to measure the depth of penetration by a medium into a polymer. The accuracy of the measurement of penetration depth is  $\pm 5$  microns.

When studying diffusion with indicators, much emphasis must be given to their selection. The indicators themselves are complex organic compounds that show different colors depending on the hydrogen ion concentration. A change in the indicator color with change in the pH of a medium takes place gradually, i.e., the change in indicator color is detected at certain pH values. The interval between two pH values found for each indicator is called the range of transition or the transition interval.

One must select indicators with which the minimum concentration of the medium penetrating into a material can be determined. In addition, the indicator must not react in a solution of organic compounds. The most appropriate indicator concentration is 0.1-0.2 percent.

The method of adding the indicator to a polymer has the disadvantage that the structure of the material changes somewhat owing to the filler added. To some extent this must affect the coefficient of diffusion. The method of "developing" thin sections in a solution of indicator eliminates this disadvantage. In addition, this method does not require special specimen preparation. However, its use in several cases is difficult owing to the impossibility of making sections of brittle polymers, for example, epoxy and polyester compounds, and also certain glass-reinforced plastics. It must be noted that when these two methods were compared with several materials, no appreciable difference in results was uncovered. Fig. 48 presents the penetration depth of hydrochloric acid in ED-5 epoxy resin as a function of exposure time. As we can see, the diffusion of the acid becomes greater with increase in concentration. The temperature function of the diffusion coefficient is exponential in nature:

$$D = D_0 e^{-\frac{E_D}{RT}}, \quad (37)$$

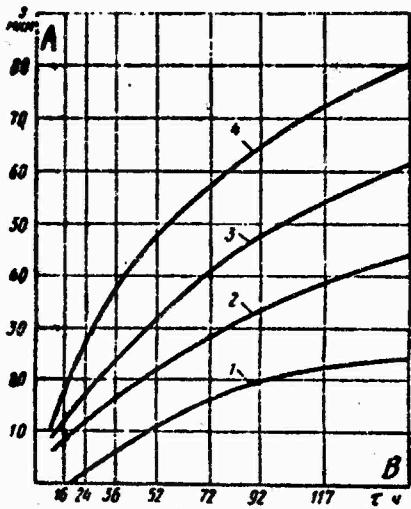


Fig. 48. Exposure dependence of depth of penetration by hydrochloric acid at different concentrations into ED-5 epoxy resin ( $t = 500^\circ\text{C}$ ):

1 — 5 % HCl  
2 — 10 % HCl  
3 — 15 % HCl  
4 — 20 % HCl

KEY: A — Microns  
B —  $\tau$ , hours

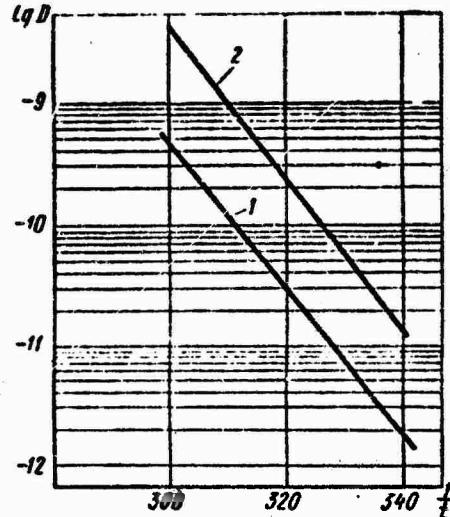


Fig. 49. Temperature dependence of the coefficients of diffusion of acid into 30 percent sulfuric acid (curve 1) and 30 percent hydrochloric acid (curve 2)

where  $D_0$  is the pre-exponential cofactor;

$E_D$  is the energy of activation of the diffusion process;

R is the universal gas constant; and

T is the absolute temperature.

This function can be represented with a straight line in the coordinates  $\lg D - 1/T$  (Fig. 49).

The microscopic method of determining the depth of penetration by a medium into a polymer we have described enables us using an indicator to determine the specific front of the specific concentration of the medium or to determine the pH at which the indicator changes its color. These methods allow us to study the kinetics of diffusion processes and to determine the effect various factors have on the diffusion coefficient. However, they do not permit us to determine the coefficient of permeability P, i.e., to determine the amount of substance passing through a layer of the polymer per unit time.

The electrochemical method of diffusion tests can be used to determine the coefficient of permeability and the coefficient of diffusion. This method is based on measuring the change in the electrical resistance of doubly distilled water separated from the test electrolyte by a membrane made of the test material. The electrical resistance of doubly distilled water is  $(5 - 7) \cdot 10^6$  ohm.

As soon as the first ions of the medium penetrate doubly distilled water, resistance drops off, i.e., electric conductivity rises. The curve "amount of penetrating electrolyte versus time" has two sections: ab is the nonsteady state process and bc is the steady state process of penetration (Fig. 50). The section bc is linear, and from it we can calculate the coefficient of permeability P:

$$P = \frac{Qd}{St}, \quad (38)$$

where Q is the amount of penetrating electrolyte in g/hr;  
S is the area of the membrane in contact with the medium, in  $\text{cm}^2$ ;  
d is the membrane thickness in cm; and  
T is the time in seconds.

The amount of penetrating electrolyte Q is determined by plotting the calibration curve "solution electroconductivity versus concentration of medium."

The experiment is conducted in a special electrochemical cell (Fig. 51) consisting of two glass half-cells, in one of which two platinum electrodes with platinum black deposited on them are soldered. A disk of the test material is squeezed between the half-cells using polytetrafluoroethylene spacers. Doubly distilled water is poured into the half-cell containing the electrolytes, and into the other half-cell -- the test electrolyte whose resistance is being measured. The disadvantage of this method, limiting its use, is simultaneous diffusion in the polymer of both the electrolyte and doubly distilled water. Both diffusion fronts are encountered in the polymer; mutual mixing (solution) takes place; and the penetration rate is considerably reduced [46].

The method of radioactive isotopes [29, 78] gained wide acceptance in the study of diffusion characteristics of polymeric materials and plastics. This method gives maximum accuracy and is suitable for virtually all materials. Unfortunately, the complexity of the experiment and the specific details of its conditions limit the scope of its application.

#### Adhesion Tests

Individual elements of equipment and pipelines made of reinforced plastics are connected with each other with cemented unions based on various cementing compounds. The strength of cemented unions can be determined

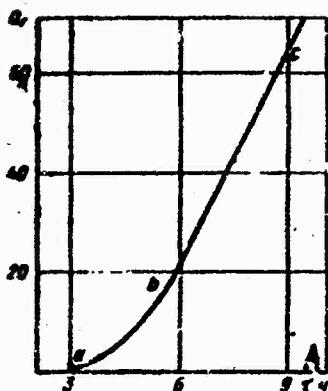


Fig. 50. Time dependence of the amount of penetrating electrolyte  
KEY:  $A$  —  $\tau$ , hours

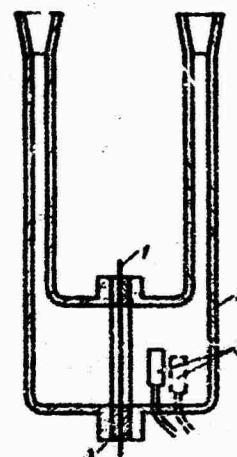


Fig. 51. Electrochemical cell for permeability tests:  
1 — specimen  
2 — half-cell  
3 — electrolyte  
4 — polytetrafluoroethylene spacers

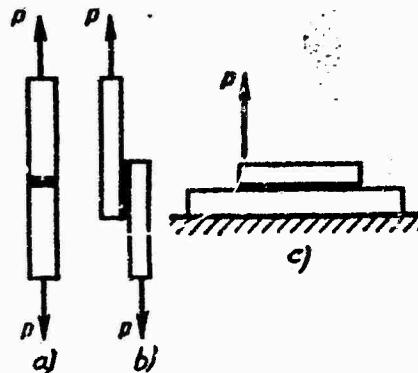


Fig. 52. Arrangement for adhesion tests:  
a — in rupture  
b — in shear  
c — in tearing

just as for mechanical tests of plastics, i.e., short-term and long-term tests in air and in corrosive media at various temperatures. Methods of corrosion testing of cemented unions are similar to corrosion testing of plastics (excluding the gravimetric method).

## CHAPTER FOUR

### STRENGTH AND TECHNOLOGICAL CALCULATIONS OF ARTICLES MADE OF REINFORCED PLASTICS

The absence of reliable engineering methods of calculating the strength of chemical equipment and pipelines made of reinforced plastics has to some extent slowed their introduction into industry. In addition, this fact has hampered the development of rational designs of articles with allowance for the optimal arrangement and distribution of the reinforcing material and binder.

The shortage of studies on the calculation of equipment and pipelines made of reinforced plastics is due to the sizable complexity of the problems. The complexity of calculating shells made of glass-reinforced plastics is explained, above all, by the presence of the structural anisotropy of the structure of the supporting framework. Additional difficulties arise since the materials from which the shell is made (glass fiber and binder) exhibit nonlinear characteristics. Some studies [41, 62, 70] on the determination of stresses when shells are loaded with internal hydrostatic pressure contain prerequisites and assumptions that reduce the reliability of the solution to the problems posed. Thus, the calculation proposed by Ganai [62] on determining the rational orientation of glass fiber in the fabrication of shells fails to allow for the combined functioning of glass fiber and binder. A simplified calculation [70] of the strength of shells based on an analysis of technological samples deliberately narrows the general formulation of the problem, not clarifying the reasons for the variation in strength properties. The author of the paper [41] does not take account of deformation properties of shells in his calculations. Binders are prepared from thermosetting resins (polyester, epoxy, and phenol-formaldehyde), therefore the assumption is made that piping geometry is not disturbed upon loading, i.e., the binding angle and the diameter remain unchanged. Actually, shells are characterized by creep, which leads to the disruption of gas-tightness upon prolonged loading.

The bearing capacity of a shell made of glass-reinforced plastics intended for service as a pressure shell often has to be estimated from the stresses in the wall when gas-tightness is disrupted. However, one

must also have reliable methods of calculating the strength of shells in order to provide for the orientation of glass fiber and its quantity so as to ensure the maximum strength and stiffness of the article. In addition, the reliable lining of the internal surfaces of equipment and piping with thermosetting plastics and sealants makes it possible to produce absolutely gas-tight shells, whose strength calculations are necessary.

This work presents several simplified methods of technological and strength calculations for shells made of reinforced plastics used in the industry and gives a partial analysis of these methods. The main disadvantages of these calculation methods include the absence of allowance for the viscoelastic properties of reinforced plastics and the inadequate consideration given to the time dependence of their strength. The theory of viscoelastic prehistory more fully describes the behavior of plastics under load. However, at the present stage thus far reliable enough analytic functions have not yet been derived for the calculation of plastics with allowance for viscoelastic prehistory. To solve the Boltzmann-Volterra relationship in the integral form [9], one must know the elastic lag factor, relaxation factor, and relaxation time. The experimental determination of these coefficients is difficult. Several theoretical problems were solved by using the theory of viscoelastic prehistory [9, 51, 65]. These relationships are in need of further improvement in estimating the properties of polymeric materials in articles.

A major contribution to the theory of anisotropic laminated shell and to the development of the optimal orientation of reinforcing materials with allowance for the action of various external loads was made by V. I. Korolev [36]. This work proposes differential equations for the strength and stability calculation of cylindrical shells when exposed to concentrated and uniformly distributed loads, which can be used in calculating chemical equipment and pipelines.

In most cases existing engineering, technological, and strength calculations of articles made of reinforced plastics are based on one of two main principles. One assertion (the "smearing" principle) [1] is based on the fact that the number of reinforcing elements is quite large and that the reinforcing material can be approximately replaced by some quasi-homogeneous anisotropic material. This material is the generalization of the classical medium considered in the anisotropic theory of elasticity. The initial necessary parameter for calculating equipment made of this material is the ultimate strength in short-term or long-term loading.

Another principle is the examination of the material with the effect of binder disregarded [57]. Here it is assumed that the fiber takes the entire load. The orientation and number of required fibers in the material of the article is determined from the condition that loading is taken simultaneously by all fibers. Local effects at the boundary of the reinforcing material and binder are neglected in this case.

## Approximate Functions Used in Calculating Reactors and Piping Made of Reinforced Plastics

Cylindrical reaction equipment and pipelines made of reinforced plastics can be thin-walled, thick-walled, and with moderate wall thickness.

The building capacity of cylindrical pressure shells is determined mainly by the resistance to internal hydrostatic pressure, which in the general case causes the body-stressed state of the walls. Of the three components of body-stressed state (normal stresses in the tangential, axial, and radial directions), the normal stress in the tangential direction is the greatest.

In practice [31], the following functions are used in calculating the largest normal stresses in the tangential direction induced in the walls of cylindrical equipment and piping when acted on by internal hydrostatic pressure  $p$  in  $\text{kg}/\text{cm}^2$ .

The Lame function is used for equipment and piping with any wall thickness (most often, for thin-walled piping):

$$\sigma_t = p \frac{1+k^2}{1-k^2}; \quad (39)$$

where the coefficient  $k = d/D = r/R$  (here  $d$  is the inner diameter of the shell and  $D$  is the outer diameter of the shell).

The Kessel, Naday, and Barlow formulas are used for thin-walled equipment and piping, assuming the wall-thickness stress distribution to be uniform:

$$\sigma_t = p \frac{d}{2t} = p \frac{r}{t} = p \frac{k}{1-k}; \quad (40)$$

$$\sigma_t = p \frac{d_{av}}{2t} = p \frac{r_{av}}{t} = p \frac{1+k}{2(1-k)}; \quad (41)$$

$$\sigma_t = p \frac{D}{2t} = p \frac{R}{t} = p \frac{1}{1-k}; \quad (42)$$

here  $t$  is shell wall thickness; and

$d_{av}$  and  $r_{av}$  are the mean diameter and mean radius of the shell, respectively.

The Kessel (Laplace), Barlow, and Naday formulas, arbitrarily assuming the uniform distribution of stresses in wall thickness, are approximate, where the Kessel formula gives understated stress values, and Barlow formula — overstated stress values. The result obtained by using the Naday formula corresponds to the arithmetic mean of stresses calculated based on the two other functions. This stress value obeys the Lame function.

The calculation of equipment and piping made of glass-reinforced plastics by approximate formulas is simpler than by the Lame formula, therefore they are used more often in engineering. But often these approximate functions are used without cognizance of the limits to their use. It is important for practical calculations to know within what limits the approximate formulas (40), (41), and (42) give an acceptable agreement with the Lame formula.

Here it is useful to divide all equipment and pipelines into three groups: thin-walled with  $0.95 \leq k < 1$ ; with mean wall thickness at  $0.65 \leq k \leq 0.95$ ; and thick-walled, for  $0 < k \leq 0.65$ .

Error analysis showed that all three approximate formulas are suitable for thin-walled pipes, since the deviation of calculation results with the Lame formula does not exceed 3 percent. Functions (40) and (41) give understated stress values of 24.3 and 4.3 percent, respectively, for shells with mean wall thickness, while formula (42) gives values overstated by 16 percent. Therefore, formula (41) can be used for practical calculations of shells with average wall thickness, yielding stress values understated by less than 5 percent.

For a more justified determination of stresses in piping walls, when using the functions the reinforcement factor of the glass-reinforced plastic must be taken into account. The thickness of the shell wall does not always reflect its bearing capacity. It can remain unchanged while the reinforcement factor of the glass-reinforced plastic is varied. The reinforcing factors refine the Lame function in the determination of calculated stresses in the walls of shells made of reinforced plastics.

#### Technological Calculation of Cylindrical Pressure Shells Made of Glass-Reinforced Plastics With Longitudinal-Transverse Lay-up of Reinforcing Material

This calculation method is suitable only for cylindrical shells with orthogonal or near-orthogonal lay-up of the reinforcing material. The calculation is made for shell structure elements.

The following main assumptions are adopted:

The shell is considered as a thin-walled cylinder with bottoms, loaded by internal pressure and flexural moment for wall thickness smaller or equal to  $0.1 D$ , where  $D$  is the outer shell diameter;

external loads applied to the shell are taken by the reinforcing material (glass fiber yarn) and the binder does not participate in taking the loading;

axial forces in the shell wall are taken completely by the longitudinal layers of the reinforcing material, and the tangential force that is taken only by the hoop layers;

the reinforcing material has a single tension value;

upon loading, there is no shear in the transverse layers of the reinforcing material related to the longitudinal layer; and

the adhesion between the reinforcing material and the polymer binder is sufficiently high so that both components have the same deformation when the shell is loaded.

Calculation of the structure elements of layers with the hoop lay-up of the reinforcing material (glass fiber yarn\*) is carried as follows.

The total force acting on a shell segment 1 cm long is determined in the hoop direction:

$$P = pd, \quad (43)$$

where  $p$  is the calculated internal pressure in  $\text{kg}/\text{cm}^2$  with allowance for the strength safety margin.

This force, according to the assumptions made, is taken by the hoop layers of the glass fiber yarn. The overall of breaking force of the glass fiber yarn  $P$  laid in the circular direction for a given shell segment is

$$P = 2N_h S \varphi n, \quad (44)$$

where  $N_h$  is the total number of glass fiber yarn laid in the hoop direction for a shell segment 1 cm long;

$S$  is the breaking force of the glass filament in kg;

$n$  is the number of plies of the glass filament in the yarn; and

$\varphi$  is the strength-use factor of the glass filament in the yarn (Table 21).

By the functions (43) and (44), the following equality is formulated:

$$pd = 2N_h S \varphi n. \quad (45)$$

The total number of glass fiber yarns laid in the hoop layers is as follows for a 1 cm long shell segment:

$$N_h = \frac{pd}{2S \varphi n}. \quad (46)$$

In addition, we can write

$$N_h = i_h M_h, \quad (47)$$

where  $i_h$  is the number of hoop glass fiber yarns in one layer for a 1 cm long shell segment; and

$M_h$  is the number of layers with the hoop glass-yarn lay-up scheme.

---

\* [yarn = roving]

TABLE 21. CHARACTERISTICS OF GLASS YARNS [50]

Число сложения нити	Метрический номер жгута	Разрывное усилие жгута в кг	Коэффициент ис- пользования про- ности нити в жгуте	1		Метрический номер жгута	Разрывное усилие жгута в кг	Коэффициент ис- пользования про- ности нити в жгуте
				Сухой жгут	Склесенный жгут			
7	3,4	11,7	0,92	7	3,26	14,5	0,94	
10	2,5	20,4	0,94	10	2,38	21,4	0,95	
20	1,23	30,5	0,75	20	1,13	34,1	0,88	
60	0,41	84,2	0,70	—	—	—	—	

KEY: 1. Number of filament plies  
 2. Metric number of yarn  
 3. Breaking strength of yarn in kg  
 4. Strength use factor of filament in yarn  
 5. Dry yarn  
 6. Cemented yarn

The number of hoop glass yarns is

$$i_h = \frac{l}{a_h}, \quad (48)$$

where  $a_h$  is the distance between axes of neighboring hoop glass yarns of the same layer (for example,  $a_h = 0.25 - 0.3$  cm for glass yarns in 30 plies).

From equality (47) we find

$$M_h = \frac{N_h}{i_h}. \quad (49)$$

The width of unidirectional tape B consisting of  $m$  glass yarns laid simultaneously in the hoop direction is determined from the equality

$$B = \pi d \operatorname{tg} \beta, \quad (50)$$

where  $d$  is the inner diameter of the shell in cm; and  
 $\beta$  is the pitch angle of the glass hoops during winding (the angle  $\beta$  is within the limits  $2\text{--}5^\circ$  for longitudinal-transverse lay-up, and less often — to  $8^\circ$ ).

Then

$$a_h = \frac{\pi d \operatorname{tg} \beta}{m}, \quad (51)$$

$$l_h = \frac{m}{\pi d \operatorname{tg} \beta}. \quad (52)$$

The calculated thickness of the shell wall corresponding only to the hoop layers of glass yarns is

$$t_h = \frac{\rho d}{2\sigma_{gu}\varphi}, \quad (53)$$

where  $\sigma_{gu}$  is the tensile strength of the glass filament in  $\text{kg}/\text{cm}^2$ .

Experimentally,  $t_h$  is determined by the formula

$$t_h = t_f M_h, \quad (54)$$

where  $t_h$  is the thickness of one hoop layer of glass yarn in cm.

Thus, formulas (43) to (54) enable us to calculate the structural elements of the hoop layers of glass yarn and the number of layers as the function of the internal pressure, shell dimensions, and fabrication technology.

The structure elements of layers with the longitudinal lay-up of the reinforcing material are calculated in similar fashion.

The force acting on the longitudinal glass yarn in the transverse direction of the shell is

$$P = p \frac{\pi d^2}{4} + \frac{M_{be} FD}{4J}, \quad (55)$$

where  $M_{be}$  is the bending moment induced by the weight of the shell containing the working liquid, in  $\text{kg} \cdot \text{cm}$ ;  
 $J$  is the moment of inertia of the shell section in  $\text{cm}^4$ ;  
 $d$  is the inner diameter of the shell in cm;  
 $D$  is the outer diameter of the shell in cm; and  
 $F$  is the cross-sectional area of the shell in  $\text{cm}^2$ .

The moment of inertia is

$$J = \frac{\pi(D^4 - d^4)}{64}. \quad (56)$$

After inserting the values of  $M_{be}$ ,  $F$  and  $J$ , equality (55) becomes as follows:

$$P = p \frac{\pi d^2}{4} + \frac{q_{sh} + q_f}{200} \cdot \frac{Dl^2}{D^2 + d^2}, \quad (57)$$

where  $q_{sh}$  is the weight of a shell 1 m in length, in kg;

$q_f$  is the weight of the liquid in a shell 1 m in length, in kg; and

$l$  is the length of the horizontal shell between two supports in cm.

The overall breaking force of glass yarn laid in the longitudinal direction is

$$P_1 = S\varphi n N_{lo}, \quad (58)$$

where  $N_{lo}$  is the number of longitudinal glass yarn in the cross-sectional area of the shell.

The combined solution of equations (57) and (58) enable us to derive a working formula for determining the total number of longitudinal glass yarn:

$$N_{lo} = \frac{\pi p d^3}{4 S\varphi n} + \frac{q_{sh} + q_f}{200} \cdot \frac{Dl^2}{(D^2 + d^2) S\varphi n}. \quad (59)$$

Setting  $d \approx D$ , we get

$$N_{lo} = \frac{314pd^3 + l^2(q_{sh} + q_f)}{400S\varphi nd}. \quad (60)$$

On the other hand,

$$N_{lo} = i_{lo} M_{lo}. \quad (61)$$

The number of longitudinal glass yarn in a single layer is

$$i_{lo} = \frac{\pi d}{a_{lo}}, \quad (62)$$

where  $a_{lo}$  is the distance between axes of neighboring glass yarn in the same layer; and

$M_{lo}$  is the total number of longitudinal layers of glass yarn.

After inserting into formula (59) the value

$$D = d + 2t$$

and performing the necessary transformations, we arrive at the analytic function for determining the thickness of the shell wall for the longitudinal lay-up of glass yarn:

$$t_{lo} = \frac{-2(2Ad - l^2) + \sqrt{[2(2Ad - l^2)] + 16A(dl^2 - 2Ad^2)}}{8A}. \quad (63)$$

where

$$A = \frac{200SpnN_{lo} - 157pd^2}{q_{sh} + q_f}. \quad (64)$$

Experimentally,  $t_{lo}$  is determined by the formula

$$t_{lo} = t_g M_{lo}, \quad (65)$$

where  $t_g$  is the thickness of a single layer of longitudinal glass yarn in cm.

The total thickness of the shell wall is

$$t_{tot} = t_h + t_{lo} = t_g(M_h + M_{lo}). \quad (66)$$

The thickness of the shell wall, with allowance for the given ratio of reinforcing material and binder, can be calculated for the case when each shell layer consists of glass yarn impregnated with binder and laid parallel to each other.

An element of the normal cross-section of arbitrary thickness can be isolated from a single shell layer. Assuming that qualitatively the glass-reinforced plastic produced is free of flaws and other inclusions, let us find the cross-sectional area of the element:

$$F = F_{bi} + F_{gl}, \quad (67)$$

where  $F_{bi}$  is the cross-sectional area of the binder in the isolated element, in  $\text{cm}^2$ ; and

$F_{gl}$  is the cross-sectional area of the glass fiber in  $\text{cm}^2$ .

The cross-sectional area of the glass fibers is

$$F_{gl} = \frac{n_t}{100N_{sp}q_f}, \quad (68)$$

where  $n_1$  is the number of unidirectional glass yarn in the element;

$N_m$  is the metric number of glass yarn in m/g; and

$\rho_{gl}$  is the density of the glass in g/cm<sup>3</sup>.

We know that

$$\frac{V_{bi}}{V_{gl}} = \frac{F_{bi}}{F_{gl}} = \frac{x\rho_{bi}}{(100-x)\rho_{gl}}, \quad (69)$$

where  $V_{bi}$  is the binder content in percent by volume;

$V_{gl}$  is the glass content in percent by volume;

$x$  is the content of binder in percent by weight; and

$\rho_{bi}$  is the density of the binder in g/cm<sup>3</sup>.

Inserting in equation (67) the values of  $F_{bi}$  and  $F_{gl}$  from formulas (69) and (68), we get

$$F = \frac{n_1}{100N_m a_i} \left( 1 + \frac{\rho_{bi}}{\rho_{gl}} \frac{x}{100-x} \right). \quad (70)$$

Substituting the values  $F = a_i n_1 t_i$ ,  $\rho_{gl} = 2.5$  g/cm<sup>3</sup>, and  $\rho_{bi} = 1.25$  g/cm<sup>3</sup> in equation (70), let us determine the thickness of a single layer:

$$t_i = \frac{1}{250N_m a_i} \left( 1 + \frac{2x}{100-x} \right), \quad (71)$$

where  $a_i$  is the distance between the axes of neighboring glass yarns in a layer, in cm.

For  $x = 50$  percent by weight (the recommended content of binder in glass-reinforced plastics for chemical equipment and piping), we have

$$t_i = \frac{3}{250N_m a_i}. \quad (72)$$

After inserting into formula (71) the average value of  $a_i$  for layers with hoop ( $a_h$ ) and longitudinal ( $a_{lo}$ ) lay-up glass yarn, the corresponding values for the shell wall thickness in the hoop  $t_h$  and longitudinal  $t_{lo}$  layers are determined.

The total thickness of the shell wall is determined from the equation

$$t_{\text{tot}} = t_h + t_b. \quad (73)$$

This calculation method is simple and applicable for determining the calculated technological parameters in fabricating shells (wall thickness, number of layers of reinforcing materials, and so on). However, it does not allow for an increase in the strength of the reinforcing material resulting from its impregnation with binder. According to the data of Van Fo Fy and N. V. Kulikov, the strength of glass yarn in plastics can be augmented by a factor of 1.6-2.3, depending on the quality of impregnation. Studies made on piping fabricated by longitudinal-transverse winding of glass yarn using polyester binder showed some agreement of experimental data with calculated values (the deviations amount to 15-20 percent). This calculation enables us to estimate the short-term strength of an article without allowing for its extended service.

#### Calculation of the Strength of Cylindrical Pressure Shells Made of Glass-Reinforced Plastics With Helical Lay-up of Reinforcing Material

Relationship of deformations in the principal directions. The pressure base in cylindrical shell made of glass-reinforced plastics fabricated by overlapping winding on a mandrel of glass yarn impregnated with binder is a skeleton consisting of the glass yarn mobilized in a specific position by the cured binder.

Each layer consists of a number of parallel-laid glass yarn impregnated with resin. In pipe fabrication, these layers of glass yarn impregnated with resin are laid with tension one on the other at a specific angle; after the piping is given the necessary dimensions, the billet is cured on the mandrel.

Let us examine the deformation of a shell wall composed of cross-lapped layers of glass yarn immobilized with binder.

The deformation induced when a shell made of glass-reinforced plastic is loaded with internal hydrostatic pressure can be represented as resulting from the imposition of two kinds of deformations:

deformation occurring without change in the length of the glass yarn and associated only with their mutual shearing in adjoining layers; and

deformation associated with the elongation of glass yarn with angles between them preserved.

The binder takes the main load in deformation of the first type. Deformations can attain sizeable values for relatively small stresses. Deformations of the second kind are associated with the appearance of stresses in glass yarn with relatively greater stiffness, therefore high stresses in glass yarn here correspond even to relatively small stresses.

It can be stated that during the first period of loading, deformations are induced in the skeleton elements that are associated mainly with the variation in the orientation of glass yarn and which lead to their arrangement such that the glass yarn takes the principal loading. As soon as the glass yarn is oriented in this way, the stiffness of the skeleton will increase sharply and further variation in the shell dimensions is governed mainly by the elastic deformation of the glass yarn. Considering the significantly greater stiffness of the skeleton compared with the binder, the stresses in the binder can be neglected, by assuming that the glass yarn takes the entire load in the shell.

The modulus of elasticity of polyester resins lies within the limits  $2 \cdot 10^4 - 4 \cdot 10^5 \text{ kg/cm}^2$ , and the modulus of longitudinal elasticity of the glass yarn is of the order of  $7 \cdot 10^5 - 1.3 \cdot 10^6 \text{ kg/cm}^2$ . Therefore, deformations of the wall element associated with elongation of glass yarn are extremely hampered.

Still, element deformation is possible which occurs without change in the length  $l$  of glass yarns; this is the deformation corresponding to the change in the angles of the rhombi formed by glass yarn of neighboring layers (Figs. 53 and 54).

In this type of deformation, the diagonals of the rhombi remain mutually perpendicular and, therefore, are the directions of the principal deformations [54].

We introduce the notation:

$\varepsilon_x = \Delta a/a$  is the relative deformation in the tangential direction in %;

$\varepsilon_y = \Delta b/b$  is the relative deformation in the direction of the pipe axis in %; and

$\Delta a$  and  $\Delta b$  are the absolute elongations of the semidiagonals of the rhombi.

Then, by using the relationships of the triangle (Fig. 54) isolated from the rhombi, let us write the following expression:

$$a^2 + b^2 = l^2. \quad (74)$$

It follows from the condition of the nonextensibility of glass yarn that

$$[b - (-\Delta b)]^2 + (a + \Delta a)^2 = l^2. \quad (75)$$

Equating the left sides of these equalities to each other and making transformations, we get

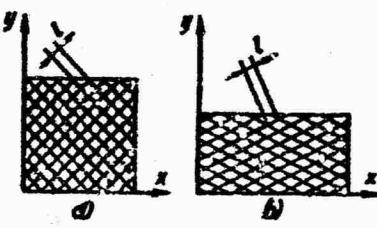


Fig. 53. Element of pipe wall:  
a — prior to deformation  
b — after deformation, with length  
of glass yarn unchanged

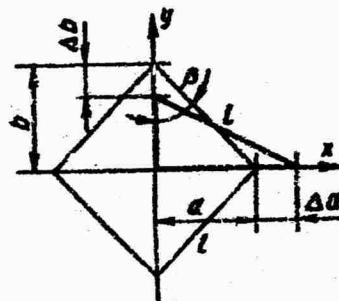


Fig. 54. Diagram for deriving the relationship between deformations in different directions of pipe made of glass-reinforced plastic fabricated by convolute winding

$$2\Delta bb + \Delta b^2 + \Delta aa + \Delta a^2 = 0. \quad (76)$$

Dividing all terms of the equality by  $b^2 = a^2 \operatorname{ctg}^2 \beta$ , we get

$$2 \frac{\Delta b}{b} + \frac{\Delta b^2}{b^2} + 2 \frac{\Delta a}{a \operatorname{ctg}^2 \beta} + \frac{\Delta a^2}{a^2 \operatorname{ctg}^2 \beta} = 0, \quad (77)$$

where  $\beta$  is the angle formed by glass yarn with the direction of the y axis (the pitch angle of glass yarn).

For small displacements, the quadratic terms in this equation are extremely small compared with the linear. Therefore, from the last equation we obtain the function

$$\epsilon_x = -\epsilon_y \operatorname{ctg}^2 \beta. \quad (78)$$

Based on the assumption that the glass yarn filaments are inextensible, we can derive the relationship between axial and radial deformations of the wall of a shell made of glass-reinforced plastics.

Displacements of any point in the shell (Fig. 55) can be characterized by two quantities: the radial displacement  $\omega$  and the axial displacement  $u$ .

Since the hypothesis that glass yarn is inextensible has been adopted, the quantities  $\omega$  and  $u$  are interrelated [10, 42].

Let us consider the glass yarn length element  $dl$ , whose projection in the circumferential and axial directions prior to shell deformation are

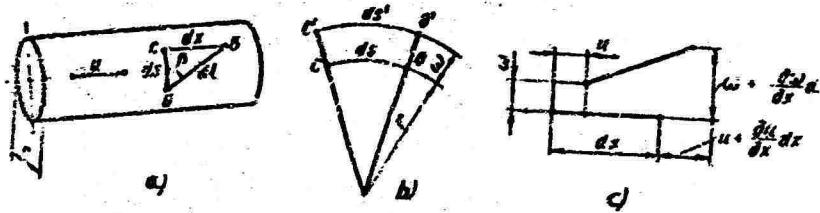


Fig. 55. Calculation scheme of the displacement of pipe element points (a) in the radial direction (b), and in the tangential and axial (c) directions with pressure loading

equal to  $ds$  and  $dx$ , respectively. After deformation,  $ds$  and  $dx$  are transformed, respectively, into the quantities

$$ds' = ds \left(1 + \frac{\omega}{r}\right); \quad (79)$$

$$dx' = dx \sqrt{\left(1 + \frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial \omega}{\partial x}\right)^2}. \quad (80)$$

The new element length  $dl'$  is determined from the equality

$$\begin{aligned} (dl')^2 &= (ds')^2 + (dx')^2 = ds^2 \left(1 + \frac{\omega}{r}\right)^2 + \\ &+ dx^2 \left[\left(1 + \frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial \omega}{\partial x}\right)^2\right]. \end{aligned} \quad (81)$$

Since the length of glass yarn filaments remains unchanged,

$$\begin{aligned} (dl')^2 &= dl^2 = ds^2 \left(1 + \frac{\omega}{r}\right)^2 + \\ &+ dx^2 \left[\left(1 + \frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial \omega}{\partial x}\right)^2\right]. \end{aligned} \quad (82)$$

Dividing both sides of the equality by  $dl^2$  and considering that

$$\frac{ds}{dl} = \cos \beta \quad \text{and} \quad \frac{dx}{dl} = \sin \beta,$$

we can write

$$1 = \left(1 + \frac{\omega}{r}\right)^2 \cos^2 \beta + \left[\left(1 + \frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial \omega}{\partial x}\right)^2\right] \sin^2 \beta.$$

After the transformation, we get

$$\left[2\frac{\omega}{r} + \left(\frac{u}{r}\right)^2\right] \cos^2 \beta + \left[2\frac{du}{dx} + \left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial r}\right)^2\right] \sin^2 \beta = 0. \quad (83)$$

This equation expresses the relationship between  $u$  and  $\omega$ , where the glass yarn length remains unchanged.

Assuming that the quadratic terms in equation (83) are equal to zero, this equation becomes transformed as follows:

$$\frac{\omega}{r} = -\frac{du}{dx} \operatorname{tg}^2 \beta, \quad (84)$$

where  $\omega/r = \epsilon_r$  is the relative radial deformation of the shell; and  $du/dx = \epsilon_x$  is the relative axial deformation of the shell.

Then

$$\epsilon_r = -\epsilon_x \operatorname{tg}^2 \beta. \quad (85)$$

The magnitude of deformations associated with the elongation of glass yarn is extremely small compared with the overall deformation caused by shell loading.

Therefore, when calculating equipment and piping made of glass-reinforced plastics, we can assume without appreciable error that glass yarn are inextensible and that the deformations in the direction of the rhombal diagonals are uniquely possible.

As the second principal hypothesis, let us assume that stresses in the resin are extremely small compared with stresses in glass yarn and that, therefore, the skewing deformations of the rhombi occur without significant energy expenditure.

This means that shells made of glass-reinforced plastics can be considered as inextensible networks with rhombic shells.

Experience shows that these hypotheses of the inextensibility of glass yarn elements and the smallness of stresses in resin provide an accuracy of the calculation of chemical equipment and piping made of glass-reinforced plastics of a given design that is suitable for practical purposes.

In some cases, when necessary, the extensibility of glass filaments and also the energy expended in the deformation of the binder can be taken into account.

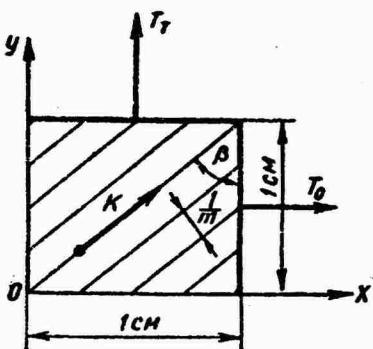


Fig. 56. Scheme of pipe element for the determination of the equilibrium pitch angle of glass yarns

Determination of the equilibrium pitch angle of glass yarn. Let us assume that glass yarns are inextensible up to the moment of shell rupture [72]. We must consider that glass yarn can shift with loading, by changing the pitch angle  $\beta$  (Fig. 56).

The loads  $T_P$  and  $T_O$  are expended not per unit length of the glass yarn layers. The resultant  $K$  of the forces  $T_P$  and  $T_O$  depends on the angle  $\beta$ ; therefore, we must obtain the ratio  $T_P/T_O$  as a function of  $\beta$ . If we let  $m$  stand for the lay-up density of glass yarn, the length occupied by each glass yarn in the direction of the generatrix will be  $1/m \cos \beta$ , and  $1/m \sin \beta$  -- in the peripheral direction of the cross-section. Per cm of length in the generatrix direction,  $m \cos \beta$  of the glass yarn of one layer is present, and  $m \sin \beta$  of glass yarn of one layer is present in the peripheral direction.

If  $K$  is taken as the load in kg per glass yarn, the component of this load in the generatrix direction ( $x$  axis) is  $K \sin \beta$ , and  $K \cos \beta$  in the peripheral direction ( $y$  axis).

Therefore, the load  $T_P$  of one glass yarn layer per cm of generatrix length will be

$$T_P = Km \cos^2 \beta. \quad (86)$$

The load on a single glass yarn layer  $T_O$  per cm of the peripheral direction is

$$T_O = Km \sin^2 \beta. \quad (87)$$

Dividing equation (86) by equation (87), we get

$$\frac{T_r}{T_e} = \operatorname{ctg}^2 \beta. \quad (88)$$

We know that when internal pressure acts against the walls of a cylindrical shell, the load ratio  $T_r/T_0$  is 2. But this ratio is observed only for one specific direction of glass yarn winding (in the case of crossover helical winding), when the following function is observed:

$$\operatorname{ctg}^2 \beta = 2. \quad (89)$$

Therefore,  $\operatorname{ctg} \beta = 1.4141$  and angle  $\beta = 35^\circ 16'$ .

Let us call this angle the equilibrium angle. A specific shell configuration must correspond to this angle. The equilibrium shell configuration can be regarded as the configuration for which the internal pressure is taken only by the glass yarn tension. If the shell is fabricated with a different angle  $\beta$ , then when the internal shell is loaded with internal pressure it tends to take on the equilibrium configuration. Thus, internal pressure can be wholly taken by glass yarn only if their angle of inclination to the peripheral direction, for helical crossover winding, will be  $35^\circ 16'$ .

If we fabricate a shell with a different glass yarn pitch angle, when subjected to internal pressure the shell will be deformed in such a way that the glass yarn pitch angle will tend to the equilibrium value. If the shell is fabricated with a glass yarn pitch angle greater than  $\beta = 35^\circ 16'$ , when exposed to pressure it will diminish (Fig. 57). In this case, piping will increase diametrically and become shortened. When piping ( $\beta > 35^\circ 16'$ ) is tested at constant pressure, the pitch angle will become less with time (Fig. 58). For an angle smaller than  $\beta = 35^\circ 16'$ , the shell will be elongated and smaller in diameter. Therefore in any case when the shell will be fabricated with a glass yarn pitch angle somewhat different from the equilibrium value for service under internal pressure, it necessarily will fail in time owing to the disruption of gas-tightness. The service life of this equipment or pipeline will be determined by the deformation properties of the binder. When shells are fabricated from glass-reinforced plastics with a glass yarn pitch angle close to the equilibrium value, their service life when operating under pressure will depend on the reliability and the condition of the adhesive interaction of binder and glass fiber, and also on the glass yarn strength.

Shells with a glass yarn pitch angle of  $35^\circ 16'$ , when loaded with internal pressure, initially change little lengthwise and diametrically, but then simultaneous increase in these directions occurs with time as the result of creep. Here practically no change in the glass yarn pitch angle is observed.

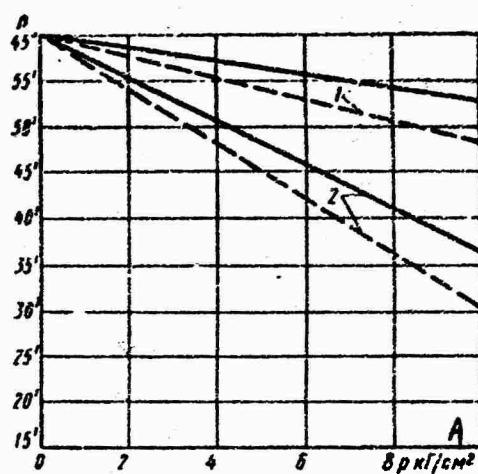


Fig. 57. Dependence of pitch angle of glass yarns  $\beta$  on internal pressure (the solid lines correspond to experimental data, and the dashed lines correspond to calculated data) for piping with inner diameter of 89 mm and wall thickness 4 mm, made of glass-reinforced plastics as follows:

- 1 -- with epoxy resin
  - 2 -- with polyester resin
- KEY: A --  $p$ ,  $\text{kg}/\text{cm}^2$

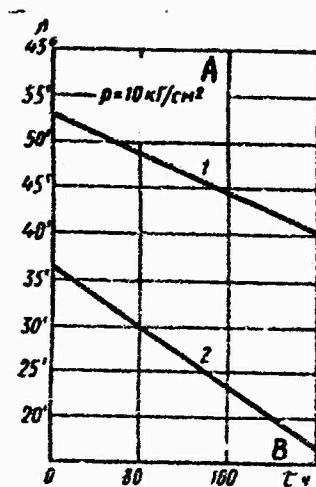


Fig. 58. Dependence of pitch angle of glass yarns  $\beta$  on the period of exposure to constant internal pressure for piping made of glass-reinforced plastics incorporation epoxy (curve 1) and polyester (curve 2) binder

KEY: A --  $\text{kg}/\text{cm}^2$   
B --  $t$ , hours

This variation in shell dimensions under internal pressure loading conditions is a consequence of two simultaneously manifested causes: the shifting of glass yarn under the effect of forces building up in the shell wall with increase in pressure, and the stretching of glass yarn owing to their increasing loading. Forces developing in the shell wall which is laminar in structure, due to the presence of pressure, are the cause of glass yarn shifting. The displacement continues theoretically until the glass yarn takes on the direction coinciding with the direction of internal force in the shell wall. But in practice, the displacement of glass yarn shows up to a greater or less extent, depending on the shear stiffness of the framework. The latter factor is due to the following: the kind and density of lay-up of glass yarn, the structural (initial) angles  $\beta$ , the number of glass yarn bearing layers, and type of binder, and so on.

Calculation of loading on glass yarn and the general equation for pipe calculations. The following relations are known for determining forces per linear unit in layers of the glass yarn in a thin-walled cylindrical shell made of glass-reinforced plastic loaded with internal pressure ( $r$  is the internal radius of the piping):  $T_0 = pr/2$  is the axial force per unit length; and  $T_T = pr$  is the tangential (peripheral) force.

From these equations there follows the ratio  $T_T:T_0 = 2$  that is representative of thin-walled cylindrical pressure shells. In the strength calculations of pressure equipment and piping made of glass-reinforced plastics, in determining the number of layers forming the framework, one must allow for the  $T_T:T_0$  ratio, as well as the structural features of the framework, by introducing the corrective coefficients corresponding to them (especially in the case of large wall thickness when  $b > 0.1 r$ ).

With reference to these relationships, one can determine the load  $K$  taken by the glass yarn by expressing it in terms of the tangential  $T_T$  or axial  $T_0$  load, density  $m$ , and angle  $\beta$  from equality (86):

$$K = \frac{T_r}{m_b \cos^2 \beta}. \quad (90)$$

Considering that  $T_T = pr$ , we get

$$K = \frac{pd}{2m_b \cos^2 \beta}, \quad (91)$$

or

$$K = \frac{\psi d}{\phi m_b}, \quad (92)$$

where  $d$  is the internal diameter of the piping prior to loading in cm;  $m_b$  is the lay-up density of the glass yarn prior to loading in  $\text{cm}^{-1}$ ; and  $\psi$  is a coefficient.

Assuming, with allowance for the unevenness of the glass yarn that  $K = K_f$  [ $f$  = fiber], let us find the burst pressure for an actual piping with number of glass yarn layers  $i$ :

$$p_f = \psi \frac{m_b K_f i}{d} [c]. \quad (93)$$

When  $\beta_f = \beta_0$ ,  $\psi = 1.333$ ; when  $\beta_f < \beta_0$ , the coefficient has the values  $2 \cos^2 \beta$  and  $4 \sin^2 \beta$ , the smaller of which determines the calculated value  $p_f$ .

The overall value of the corrections is [c]

$$[c] = [c_1] [c_2] [c_3] [c_4] [c_5]. \quad (94)$$

These cofactors reflect the effect of the piping wall design, fabrication technology, and the kind of loading.

To allow for long-term service of pressure piping made of glass-reinforced plastics with a given design, the working pressure is calculated with allowance for the strength safety margin  $n$ :

$$p_w = \psi \frac{m_b K_{fl}}{dn} [c]_D \quad (95)$$

where  $[c]_D = [c] [c_6] [c_7]$  are the coefficients allowing for long-term loading of piping with internal pressure.

The safety margin factor, based on literature data, varies from 5 to 10.

Corrective coefficients in the calculation equation. When calculating multi-ply piping made of glass-reinforced plastics, corrective coefficients are introduced that allow for changes in the operating conditions of an article compared with thin-walled shells [43]. These coefficients must be geometrically or physically meaningful and can be established by direct experiment independently of each other. They can be introduced in calculation equations in various combinations, depending on the framework design adopted and simplifying assumptions.

The cofactor  $c_1$  is a function of the angle  $\beta$  and allows for change in the piping diameter due to displacement of glass yarn when pressure is received, i.e., with variation in the angle  $\beta$  from  $\beta_h$  [h = hoop] to  $\beta_f$  [f = fiber] (if  $\beta_f$  differs from  $\beta_0 = 35^\circ 16'$ ) (Fig. 59). From the figure it follows that

$$\pi d_{\beta_b} = 1 \cdot \cos \beta_b \quad (96)$$

and

$$\pi d_{\beta_h} = 1 \cdot \cos \beta_h \quad (97)$$

Hence

$$\frac{d_{\beta_b}}{d_{\beta_h}} = \frac{\cos \beta_b}{\cos \beta_h}$$

or

$$d_{\beta_b} = d_{\beta_h} \frac{\cos \beta_b}{\cos \beta_h}.$$

Therefore,

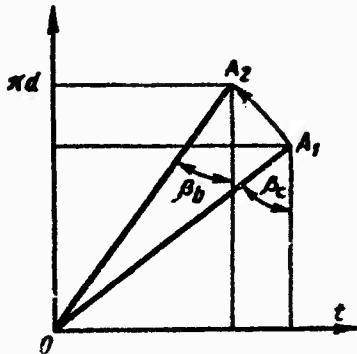


Fig. 59. Calculation scheme of the shifting of glass yarns

$$c_1 = \frac{\cos \beta_b}{\cos \beta_h}. \quad (98)$$

If  $\beta_f = \beta_0$ ,

$$c_1 = \frac{\cos 45^\circ 16'}{\cos \beta_h} = \frac{0.81647}{\cos \beta_h}, \quad (99)$$

where  $\beta_f$  is the pitch angle of glass yarn at the moment of piping rupture;

$\beta_0$  is the equilibrium angle; and

$\beta_h$  is the pitch angle of glass yarn prior to loading.

The correction  $c_2$  reflects the effect of the thickness of the cylindrical wall of piping and its reduction due to inhomogeneity of the component glass yarn layers; this correction can be separated into two cofactors:  $c_2^1$  and  $c_2^2$ . The cofactor  $c_2^1$  reflects the inhomogeneity in the loading of the glass yarn layers (from the internal to the external layers), which depends on the number of layers  $i$ , internal pipe diameter  $d$ , and layer thickness  $t_1$ . It shows what relative fraction of the resistance to hydrostatic pressure is exerted by the external layer of the glass yarn compared with the resistance exerted by the internal layer.

Let us assume that layerwise reduction in the loads occurs in the wall of a tubing of a given design, obeying the Lame function for piping open on both sides and loaded with internal pressure  $p'$  (in  $\text{kg}/\text{cm}^2$ ). Hence by finding the ratio of the tangential stresses of the last  $\sigma_t''$  and

first  $\sigma'_t$  layers and assuming the layerwise reduction to be approximately linear, we can determine

$$\sigma_t = \frac{pr^2}{R^2 - r^2} + p \frac{r^2 R^2}{R^2 - r^2} \cdot \frac{1}{r_x}, \quad (100)$$

for  $r_x = r$

$$\sigma_t' = p \frac{r^2 + R^2}{R^2 - r^2}; \quad (101)$$

for  $r_x = R$

$$\sigma_t' = \frac{2pr^2}{R^2 - r^2}, \quad (102)$$

where  $r$  and  $R$  are the internal and outer pipe radii.

Hence, by expressing radii in terms of diameters, we have

$$c_2' = \frac{\sigma_t'}{\sigma_t} = \frac{2d^2}{D^2 + d^2}, \quad (103)$$

where  $d$  and  $D$  are the internal and outer pipe diameters.

Expressing  $D$  in terms of  $d$ ,  $i$ , and  $t_h$  and introducing the notation

$$B = \frac{d}{2(i-1)t_c},$$

we obtain the possibility of calculating  $c_2'$  for any layer:

$$c_2' = \frac{B^2}{B^2 + B + 0.5}. \quad (104)$$

Based on the equation  $c_2' = \frac{4}{1 + \frac{1}{B} + \frac{0.5}{B^2}}$ , we can assume to a sufficient approximation that  $c_2'$  depends linearly on the number of layers.

The coefficient  $c_2''$  allows for the inhomogeneity of the rupture of glass yarn layers that typifies multi-ply cylindrical design. Weakened sections of glass yarn can be detected in layers, leading to a change in the above-indicated load distribution by layers and to a reduction in the mean layer strength.

This correction is expressed by the equation

$$c_3 \approx 1 - A_2(i - 1), \quad (105)$$

where  $A_2$  is an experimental coefficient.

The correction  $c_3$  allows for the deformation of glass yarn under loading when the glass yarn is present in a given structure:

$$c_3 = 1 + \epsilon_f \quad (106)$$

where  $\epsilon_f$  is the relative elongation of the glass yarn at failure.

The correction  $c_4$  reflects the effect of the rupture inhomogeneity of glass yarn in layer  $c_4'$ , the effect of adhesion, tension, and thermal exposure during curing  $c_4''$ :

$$c_4 = c_4' c_4'' \quad (107)$$

The coefficient  $c_5$  allows for the kind of piping loading during testing or service; the coefficient  $c_6$  allows for the effect of temperature conditions when pipes are in long-term service; and the coefficient  $c_7$  allows for the effect of a corrosive medium.

The overall value of the corrections [6] can also be determined experimentally for a piping of a given design.

Example. Let us determine the cofactor [6] for piping made by crossover helical winding of glass yarn in 60 plies using polyester binder.

Initial data. The rupture load for glass yarn  $K_f$  is 84.2 kg (in accordance with VTU [All-Union Technical Regulation] 91-63); the number of layers  $i$  is 8; the glass yarn lay-up density  $m_h$  is  $5 \text{ cm}^{-1}$ ; the internal pipe diameter  $d$  is 8 cm; the pitch angle of glass yarn during winding  $\beta$  is  $30^\circ$ ; and the internal burst hydrostatic pressure for short-term loading (experimental value)  $p_{in}$  is  $370 \text{ kg/cm}^2$ . When  $\beta$  is  $30^\circ$ , the coefficient  $\psi$  is

$$\psi = 4 \sin^2 \beta = 4 \sin^2 30^\circ = 1.$$

According to function (93), the calculated value of the internal burst pressure is

$$p_{th} = \psi \frac{m_h K_f}{d} [c] = 1 \frac{5 \cdot 84.2 \cdot 8}{8} [c] = 421 [c] \text{ kg/cm}^2$$

Hence, the unknown cofactor can be determined:

$$[c] = \frac{P_{th}}{421} = \frac{370}{421} = 0.87.$$

This method of calculating shells made of glass-reinforced plastics fabricated by helical crossover winding of glass yarn does not allow for the effect of bending moment, which appreciably reduce the bearing capacity of articles produced by this method of their fabrication. This situation applies with special force to pipes that in most cases of practical use are subject to bending moments. As the shell diameter is increased, this disadvantage of the suggested calculation scheme is less significant, owing to a rise in their stiffness.

#### Technological Calculation of Cylindrical Pressure Vessels Made of Glass-Reinforced Plastics With Ideal Combination Lay-up Scheme of Reinforcing Material

Vessels with ends loaded by internal hydrostatic pressure are most often fabricated of reinforced plastics by the winding method. During winding, the reinforcing fibers can be wound on the mandrel at any given angle to the vessel axis. Often, a combination lay-up scheme of the reinforcing materials is used, that is, helical winding is supplemented by longitudinal-transverse lay-up of the glass fiber. For a specific ratio of wall thicknesses corresponding to the helical, transverse, and longitudinal windings, we can also form the vessel ends. Outwater [57] established several functions that are of practical interest for calculating equipment of this type.

The following assumptions are made:

- during vessel loading, all reinforcing fibers are loaded identically;
- during loading, the bending moment in the vessel wall is absent;
- the strength of the reinforcing material of the vessel comprises the longitudinal strength of fiber, and the binder strength is neglected;
- the vessel is symmetrical and consists of a cylindrical section and two ends, one of which has a hatch in its center;
- the thickness of the cylinder wall is very small compared with its diameter. i.e., the internal and the outer diameters are provisionally identical;
- the reinforcing fibers have identical tension;
- the shearing and displacement of layers with different lay-up schemes relative to each other are impossible; and
- the fibers of each winding structure are continuous.

Analysis of the geometry of lay-up and stresses in the vessel wall is made separately for the cylindrical section and the end-closures.

The total thickness of the vessel wall  $t$  comprises the wall thickness corresponding to longitudinal winding,  $t_{lo}$ , transverse winding  $t_h$ , and crossover helical winding  $t_a$ .

The tension in the wall of a cylindrical vessel can be calculated based on two components of stresses induced for loading parallel to the vessel axis  $\sigma_1$  and in the tangential direction  $\sigma_t$ . Since the vessel is symmetrical, the principal axes lie precisely in these directions and, therefore, the shear stresses in these directions are zero. We know [57] that  $\sigma_t = 2\sigma_1$ .

Since the shell is fabricated by combination winding, when the vessel is loaded the hoop stress  $\sigma_t$  is composed of stresses in the layers of hoop winding  $\sigma'_t$  and of the tangential component of stresses in the helical winding layers. Stresses in the layers of longitudinal winding and the axial component of stresses in the layers of the helical winding act in the axial direction and do not affect the tangential stress.

The following stresses are induced in the unit element of the longitudinal section of the wall parallel to the vessel axis:

$$\sigma_l = \frac{\sigma'_t t_h}{t} + \frac{\sigma_{ta} t_a}{t}. \quad (108)$$

Stresses in the layers of hoop winding  $\sigma'_t$  are numerically equal to the tensile stresses in glass fiber. Similarly, the stress in the axial direction is

$$\sigma_l = \frac{\sigma'_l t_l}{t} + \frac{\sigma_{la} t_a}{t} \quad (109)$$

or

$$\frac{\sigma_l}{2} = \frac{\sigma'_l t_l}{t} + \frac{\sigma_{la} t_a}{t}, \quad (110)$$

where  $\sigma'_l$  represents the stresses in the layers of longitudinal winding, which are equal to the fiber strength  $\sigma$ ; and  $\sigma_{la}$  is the stress component in layers with a helical winding scheme.

From the definition it follows that

$$\sigma'_l = \sigma'_t = \sigma. \quad (111)$$

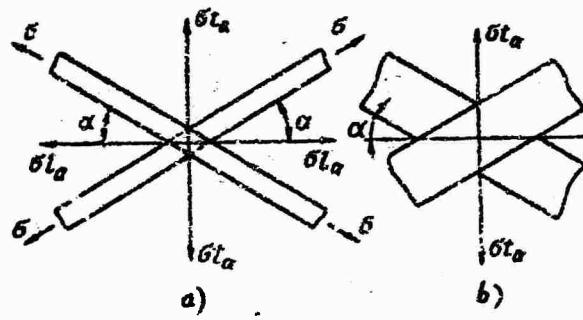


Fig. 60. Scheme of stresses acting in fibers with convolute (a) and spiral (b) winding

From Fig. 60, we can write the following expression based on an analysis of two filaments for crossover helical winding

$$2\sigma d_f \sin \alpha = \sigma_{t_\alpha} \frac{2d_f}{\sin \alpha}, \quad (112)$$

where  $d_f$  is fiber diameter; and

$\alpha$  is the glass fiber winding angle (between the fiber and the cylinder axis).

Hence,

$$\sigma_{t_\alpha} = \sigma \sin^2 \alpha. \quad (113)$$

The analogous component for helical winding is

$$\sigma_{t_\alpha} = \sigma \cos^2 \alpha. \quad (114)$$

Summing up equalities (113) and (114), we get

$$\sigma_{t_\alpha} + \sigma_{t_\alpha} = \sigma (\sin^2 \alpha + \cos^2 \alpha) = \sigma. \quad (115)$$

This condition is realized in equiloaded fibers, i.e., in an idealized vessel.

We know that

$$t = t_h + t_b + t_\alpha. \quad (116)$$

Using the functions (115) and (116), we can write

$$\sigma_t = \frac{\sigma t_b}{t} + \frac{\sigma t_a \sin^2 \alpha}{t}, \quad (117)$$

$$\sigma_t = \frac{\sigma t_b}{t} + \frac{\sigma t_a \cos^2 \alpha}{t}. \quad (118)$$

By adding equalities (117) and (118), we can show that

$$\sigma = \sigma_t + \sigma_c. \quad (119)$$

Using this function, we can obtain a formula for calculating the total thickness of the wall for an ideal vessel fabricated by winding.

We know that

$$\sigma_t = 2\sigma_i = \frac{pD}{2t}. \quad (120)$$

Hence

$$t = \frac{pD}{2\sigma_t} = \frac{pD}{4\sigma_i}. \quad (121)$$

Using equalities (119) and (120), we can show that

$$\sigma_t = \frac{\sigma}{3}. \quad (122)$$

Then equality (121) can be represented as

$$t = \frac{3}{4} \cdot \frac{pD}{\sigma}. \quad (123)$$

Since tensile fiber strength and the allowable stress, as well as the working pressure and diameter of the vessel are usually known, it is possible to calculate total wall thickness.

It must be noted that the total thickness of a vessel wall does not depend on the thickness of the constituent layers and the winding angle. However, the thickness of a layer of each winding type and the winding angle are interrelated by the fundamental geometrical relationships for a cylindrical pressure vessel given the condition that fibers are identically loaded in all winding layers. When the thickness of a layer for spherical winding at different angles is increased, the thickness of the layers of the hoop and longitudinal lay-up schemes must be reduced, with the principal ratios of the ideal cylinder under pressure kept constant. The function for the thickness of different layers is derived as follows.

Considering that  $\sigma_t = 2\sigma_1$ , and using equalities (117) and (118) we can obtain

$$\sigma t_b + \sigma t_a \sin^2 \alpha = 2\sigma t_{f_1} + 2\sigma t_a \cos^2 \alpha, \quad (124)$$

CY

whence

$$t_\alpha = \frac{2t_h - t_b}{\sin^2 \alpha - 2 \cos^2 \alpha}. \quad (125)$$

Since  $\sin^2 \alpha = 1 - \cos^2 \alpha$ , we get

$$t_\alpha = \frac{2t_h - t_b}{1 - 3 \cos^2 \alpha}. \quad (126)$$

Subtracting equality (126) from (116), let us determine  $t_{10}$ . Using equality (116), we can arrive at the resulting functions:

$$t_b = \frac{t}{3} - t_\alpha \cos^2 \alpha; \quad (127)$$

$$t_h = \frac{2t}{3} - t_\alpha \sin^2 \alpha. \quad (128)$$

In the particular case when  $t_\alpha = 0$  ( $t_{10} = t/5$  and  $t_h = (2/3)t$ ), we get  $t_h = 2t_{10}$ , which is the principal requirement for a vessel that does not have layers with helical winding where all fibers are equally loaded.

Thus, these functions enable us to calculate the cylindrical portion of a pressure vessel for optimal conditions by using different combinations of helical, longitudinal, and hoop lay-up schemes of the reinforcing material. The total vessel wall thickness depends on the type of lay-up scheme combination and can be calculated for a known vessel diameter, known strength of reinforcing material, and required working pressure. The known winding angle enables us to calculate also several other components of the total wall thickness.

The end-closures of pressure vessels made of reinforced plastics fabricated by winding are calculated on the condition that the cylindrical shell smoothly intergrades into the end-closure which is not subject to bending. With reference to the presence of a central opening, the end-closure section profile is calculated, along with its required thickness. Experience shows that longitudinal and helical winding schemes can be used in forming an end-closure, and these schemes are successfully used in fabricating the cylindrical shell of a vessel.

In the calculation, an analysis is made of the elementary section of the end-closure situated at a distance  $r$  from the vessel axis. The radii of curvature of this section in the directions shown in Fig. 61 are denoted by  $R_1$  and  $R_2$ . Suppose the total end-closure thickness  $t_e$  is composed of the thicknesses of the longitudinally and helically laid layers  $t_{e10}$  and

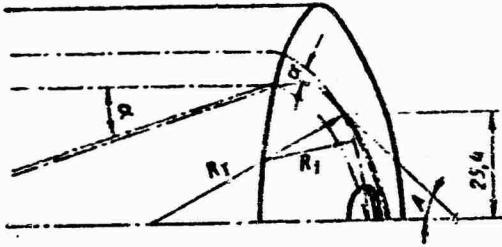


Fig. 61. Calculation scheme of vessel with bottom made of glass-reinforced plastic using glass filament winding

$t_{e\alpha}$ . Helical winding is unfeasible for end-closures owing to the slip-page of turns. The helical angle with the meridional direction is denoted by  $\alpha_e$ , and the angle between the tangent to the elementary section and the vessel axis is denoted by  $A$ . The stress components in the section in the axial and tangential directions are denoted by  $\sigma_{e\text{lo}}$  and  $\sigma_{e\text{t}}$ , respectively. The end-closure thickness here is

$$t_e = t_{e\alpha} + t_{e\text{lo}}. \quad (129)$$

In the absence of a bending moment in the end-closure,

$$\frac{\sigma_{e\text{lo}}}{R_1} + \frac{\sigma_{et}}{R_t} = \frac{P}{t_e}. \quad (130)$$

We know that

$$R_t = \frac{r}{\cos A}. \quad (131)$$

Relating this equality to the cross-sectional area of the end-closure, we can get

$$\rho\pi r^2 = \sigma_{e\text{lo}} t_{e\text{lo}} (2\pi r \cos A) \quad (132)$$

or

$$\frac{\rho r}{2t_{e\text{lo}}} = \sigma_{e\text{lo}} \cos A. \quad (133)$$

Since the number of longitudinal fibers is constant,

$$t_{el} = t_a \left( \frac{D}{2r} \right), \quad (134)$$

where  $t_{lo}$  is the thickness of layers with longitudinal winding on the cylindrical portion of the vessel.

Similarly, we can express the thickness of helically wound layers at any site on the end-closure at any distance from the axis for a given winding angle:

$$t_{ea} = t_a \left( \frac{D}{2r} \right) \left( \frac{\cos \alpha}{\cos \alpha_e} \right). \quad (135)$$

From the equilibrium condition (117) and (118), we find

$$t_e \sigma_{el} = t_{el} \sigma + t_{ea} \sigma \cos^2 \alpha_e, \quad (136)$$

and

$$t_e \sigma_{er} = t_{er} \sigma + t_{ea} \sigma \sin^2 \alpha_e. \quad (137)$$

Cancelling out  $\sigma_{el}$ ,  $\sigma_{er}$ ,  $t_{el}$ ,  $t_{ea}$ , and  $\sigma$  from these equations, we get the fundamental equality describing the end-closure geometry:

$$\frac{R_T}{R_1} = 2 - \frac{\sin^2 \alpha \left( \frac{\cos \alpha}{\sin \alpha_e} \right)}{\frac{t_{lo}}{t_a} + \cos \alpha \cos \alpha_e}. \quad (138)$$

This equation of a curve describes the relationship between  $R_T$  and  $R_1$  as a function of the thickness of the layers of each kind of winding and the winding angle. When layers with longitudinal winding are absent, the equation of the curve describing the end-closure geometry becomes

$$\frac{R_T}{R_1} = 2 - \operatorname{tg}^2 \alpha_e. \quad (139)$$

Tension in fibers is determined from the function derived on the basis of equalities (131), (133), (134), and (136):

$$\sigma = \frac{pr^2}{D \cos A (t_{lo} + t_a \cos \alpha \cos \alpha_e)}. \quad (140)$$

As we know, often vessels are wound with the reinforcing fiber lay-up calculated in accordance with a geodetic curve. This kind of winding can also ensure the forming of end-closures in accordance with equation (139).

### The equality

$$r \sin \alpha_e = \text{const.} \quad (141)$$

is the theoretical condition for winding along a geodetic line.

The constant can be determined from the condition that the filament is wound over the cylindrical portion of the vessel:

$$r \sin \alpha_e = \frac{D}{2} \sin \alpha; \quad (142)$$

This condition is valid also the end-closure.

Inserting the value of  $\alpha_e$  from equation (142) into equality (139), we can obtain an expression for the calculated curve of the end-closure profile:

$$\frac{R_r}{R_i} = 2 \left[ \left( \frac{2r}{D \sin \alpha} \right)^2 - 1 \right]^{-\frac{1}{2}}. \quad (143)$$

These analytical functions enable us to determine the optimal end-closure profile graphically in the first stage, according to equations (138) and (143). Depending on the resultant shape of the end-closure, its fabrication procedures are developed. As shown by experience, a spherical end-closure most fully corresponds to the requirements imposed. According to the profile of an end-closure obtained graphically, templates are built with which the end surfaces of mandrels are fabricated for vessel construction.

### Strength Calculations of Chemical Equipment and Piping Made of Glass-Reinforced Plastics by the Method of Approximations

In calculating articles made of glass-reinforced plastics, we must start from the condition that they are subjected to complex exposure to the ambient environment, increase temperatures, load, and other service factors.

Calculation based on the method of approximations involves setting up a series of approximations, based on experimental data, to estimate the change in the strength of the glass-reinforced plastic when exposed to these factors [82]: effect of medium, mechanical stresses, vibrations, technological parameters, and so on.

The allowable stress is determined with reference to the effect of each factor on the strength of the glass-reinforced plastic, and this stress is then introduced into the calculation.

Pipe wall thickness is determined using the formula of the American Society of Mechanical Engineers:

$$t = \frac{pr}{[\sigma]e - 0.6p} \text{ cm}, \quad (144)$$

where  $p = 1.5 P_p$  in  $\text{kg/cm}^2$  is the calculated pressure ( $P_p$  is the working pressure);  
 $r$  is the internal pipe radius in cm;  
 $e$  is the butt joint factor; and  
 $[\sigma]$  is the allowable stress in  $\text{kg/cm}^2$ , adopted with reference to approximations.

When calculating reactors with sleeving, the shell wall thickness of the sleeving is calculated using the formula

$$t = \frac{pR}{[\sigma_2]}, \quad (145)$$

where  $p$  is the pressure of the coolant in the sleeving in  $\text{kg/cm}^2$ ;  
 $R$  is the radius of the shell (sleeving) in cm; and  
 $[\sigma_2]$  is the allowable stress for the sleeving material in  $\text{kg/cm}^2$ .

The thickness of the equipment shell wall is determined as follows. The maximum allowable pressure  $p'$  is assumed to be

$$p' = 0.807 \frac{Et_1^2}{L} \sqrt[4]{\left(\frac{1}{1-\mu^2}\right)^3 \frac{r_1^2}{r^2}}, \quad (146)$$

where  $p' = 1.5 p$  is the maximum allowable pressure in  $\text{kg/cm}^2$ ;  
 $E$  is the flexural modulus of elasticity of the glass-reinforced plastic in  $\text{kg/cm}^2$ ;  
 $L$  is the length of the shell in cm;  
 $r$  is the shell radius in cm;  
 $t_1$  is the wall thickness in cm; and  
 $\mu$  is Poisson's ratio.

Hence

$$t_1 = \sqrt[10]{\frac{(p')^3 L^4 r^6}{0.807^4 E^4 \left(\frac{1}{1-\mu^2}\right)}} \text{ cm}. \quad (147)$$

Calculation based on the method of approximations is marked by a limitation on its range of application. Available approximations that allow for the effect of external factors are extremely arbitrary and do not reflect the significant diversity of existing real external exposures and conditions. Strength characteristics necessary for calculations based on this method are determined from standard or special specimens separately exposed to individual external factors during a limited test, often in an unstressed state. Therefore, the calculation for strength using approximations does not take account of the effect of the combined exposure of a number of factors, which introduces an appreciable error into the final result.

However, this calculation method can be used for articles employed in large numbers in certain known constant service conditions. In this case actual material on the approximations is used, which successively refines data obtained experimentally.

To expand the scope of application of this calculation method, we need a classification of external exposures and require an adequate handbook on approximations determined for specific materials with reference to the stressed state and interaction of factors. The reliability of calculation results will depend on how well-substantiated the existing approximations are. There are many ways of increasing the reliability of approximations based on using tested methods of extrapolating experimental data to the time corresponding to the service.

#### Simplified Method of Calculating Shells Made of Glass-Reinforced Plastics

This method enables us to estimate the strength properties of shells made of glass-reinforced plastics with allowance for the main structural-operating factors [70].

To allow for the effect of the adhesive-cohesive strength of binder on the degree to which the strength of the reinforcing material is utilized, and also the effect of a specific technological procedure of molding and curing, in the calculation use is made of data obtained from testing technological specimens in the form of tape, strip, or rings fabricated of the components intended for shell production under the same technological conditions and with the same equipment with which their fabrication is proposed. The formula use of the experimental rupture strength obtained from testing specimens instead of the introduction of various coefficients simplifies and increases the accuracy of calculations.

The following equation is used to determine the wall thickness of shells made of glass-reinforced plastics as a function of strength and anisotropy:

$$t = \frac{p}{v[\sigma]} \cdot \frac{r \left(1 + \frac{t}{r}\right)}{\left(2 + \frac{t}{r}\right)}, \quad (148)$$

where  $t$  is the shell wall thickness;  
 $p$  is the internal hydrostatic pressure in the shell;  
 $r$  is the internal shell radius;  
 $[\sigma]$  is the allowable rupture stress determined from special tests;  
and  
 $v$  is the coefficient of anisotropy.

The coefficient of anisotropy is

$$v = \frac{t_h}{t_h + t_{lo}}, \quad (149)$$

where  $t_h$  is the overall thickness of the hoop layer; and  
 $t_{lo}$  is the overall thickness of the longitudinal layers obtained in shell winding.

The optimal coefficient of anisotropy  $v = 2/3$ , and the most advantageous ratio of reinforcing layers ensuring the minimum shell weight with maximum strength is

$$\frac{t_{lo}}{t_h} = \frac{1-v}{v} = \frac{1}{2}.$$

Denoting

$$\frac{p}{[\sigma]v} = \Delta, \quad (150)$$

we get

$$\frac{t}{r} = \Delta + \sqrt{1 + \Delta^2} - 1. \quad (151)$$

The determination of the optimal wall thickness of a shell made of glass-reinforced plastic is considerably simplified if expressions (150) and (151) are represented graphically (Fig. 62). Then, we determine  $\Delta$  on a logarithmic plot for a given pressure as a function of the strength of the glass-reinforced plastic. Further, we can find the optimal wall thickness for specified pressure and strength from the value of  $\Delta$  on the plot  $t/r = f(\Delta)$ . The plot makes it possible to modify the parameters, thus simplifying their choice.

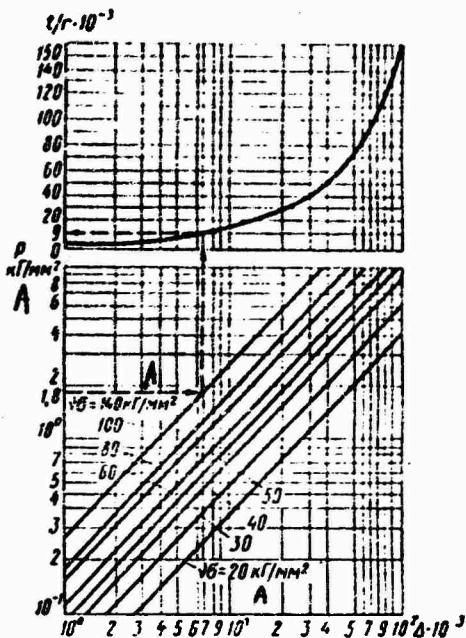


Fig. 62. Logarithmic plot for the determination of the ratio  $t/r$  for shells made of glass-reinforced plastics [70]

KEY: A --  $\text{kg}/\text{mm}^2$

However, this calculation method does not enable us to fully allow for a number of technological factors (tension, uniformity of impregnation, defect, and so on) that are difficult to reproduce on specimens in the form of samples, which can introduce a large error into results. In addition, there are not yet any reliable modeling methods for large-size articles made of glass-reinforced plastics, which to some extent reduces the reliability of using results obtained for separate technological samples in the calculations. When testing technological samples, it is difficult to reproduce the stressed state of materials of which the articles are made. This limits the application of the empirical nomograms obtained. The simplified method also does not afford the possibility of allowing for the effect of external factors on the strength of articles over the course of time.

#### Estimate of the Longevity of Pressure Piping Made of Glass-Reinforced Plastics With Allowance for a Disruption of Gas-Tightness

Piping made of glass-reinforced plastics of domestic manufacture intended for service at low pressures (to  $3-4 \text{ kg}/\text{cm}^2$ ) can be used in industry without an internal sealant layer. In this case the binder must be chemically resistant to the corrosive media being transported. Depending on the kind of corrosive medium and its temperature, the longevity of

TABLE 22. COEFFICIENTS  $m$  AND  $B$  FOR CALCULATIONS OF THE SERVICE LIFE OF PIPING MADE OF GLASS-REINFORCED PLASTICS WHEN EXPOSED TO WATER

1 Метод изготовления трубы	2 Коэффициент $m$ при температуре $\beta = 0^\circ\text{C}$			3 Коэффициент $B$ при температуре $\beta = 0^\circ\text{C}$		
	23	35	45	23	35	45
4 Намоткой стеклокугута на полиэфирном связующем в 60 сложений при $\beta = 45^\circ$	$2,56 \cdot 10^{-4}$	$2,43 \cdot 10^{-4}$	$1,35 \cdot 10^{-4}$	$4,89 \cdot 10^3$	$3,55 \cdot 10^3$	$1,31 \cdot 10^3$
5 Намоткой стеклокугута на полиэфирном связующем в 20 сложений при $\beta = 45^\circ$	$0,72 \cdot 10^{-4}$	$0,62 \cdot 10^{-4}$	$0,56 \cdot 10^{-4}$	$5,9 \cdot 10^4$	$7,25 \cdot 10^4$	
6 Намоткой стеклокугута из эпоксидного связующем в 60 сложений при $\beta = 45^\circ$	$1,25 \cdot 10^{-4}$	$1,22 \cdot 10^{-4}$	$1,2 \cdot 10^{-4}$	$7,4 \cdot 10^3$	$4,07 \cdot 10^3$	$1,17 \cdot 10^3$

- KEY:
- 1 -- Method of piping fabrication
  - 2 -- Coefficient  $m$  at listed temperature in  $0^\circ\text{C}$
  - 3 -- Coefficient  $B$  at listed temperature in  $0^\circ\text{C}$
  - 4 -- Winding of glass yarn using polyester resin in 60 plies for listed  $\beta$  value
  - 5 -- Winding of glass yarn using polyester binder in 20 plies for  $\beta = 45^\circ$
  - 6 -- Winding of glass yarn using epoxy binder in 60 plies for  $\beta = 45^\circ$

piping from the moment of loading to the moment of breakdown of gas-tightness ranges from 1 to 4 years.

When determining piping longevity, the limiting state is taken as the state for whose onset gas-tightness breaks down under conditions of prolonged exposure to constant pressure.

Since the experimental points lie near a straight line (cf. Fig. 16) in semilogarithmic coordinates, we can propose an exponential function between time prior to the breakdown of gas-tightness  $\tau$  and the normal stress in the tangential direction  $\sigma_t$ . The function approximating the long-term strength curve can be written as

$$\tau = Be^{-m\sigma_t}. \quad (152)$$

The coefficients  $B$  and  $m$  are determined by a statistical treatment of results of tests conducted over a relatively short time interval. Table 22 presents the values of these coefficients for piping made by helical crossover winding for different test conditions [18].

A comparison of the results of testing piping fabricated by cross-over helical winding of glass yarn, for short-term and long-term loading, showed that absolute values of the relative deformations corresponding to the moment of gas-tightness breakdown remain identical for each winding structure. Thus, for piping made of glass yarn in 60 plies with a  $45^\circ$  winding angle using polyester binder, the limiting deformations in the tangential direction are 0.1-1.0 percent, 0.5-0.6 percent in the axial direction, and for piping of this kind made of glass yarn in 20 plies, the values are 1.8-2 percent and 0.6-0.8 percent, respectively. As shown by tests, the creep curves of glass-reinforced plastic pipe plotted on the basis of measurements of deformations in the tangential and axial directions have three characteristic sections in the general case (Fig. 63): sections of nonsteady-state creep within whose limit the deformation rate decreases monotonely; sections of steady-state creep, where the deformation rate in these limits is constant and in a particular case equal to zero (the dashed curves separate these sections from the others); and sections with increasing deformation rate, within whose limits there is a breakdown in piping gas-tightness.

When considering the long-term strength of piping, it is not the moment of piping failure that is taken as the dangerous state, but the moment when the third stage of creep begins, which corresponds to the beginning of microcrack development. This choice of the dangerous state is accounted for not only by experimental difficulties in determining the moment of breakdown in gas-tightness, but also by physical considerations. The piping material during the breakdown of gas-tightness differs qualitatively, during a process of significant specimen deformation, from undeformed or little-deformed glass-reinforced plastic, since deformation localization takes place in the binder. Here a large number of microcracks are induced in the material, caused by the cracking of the

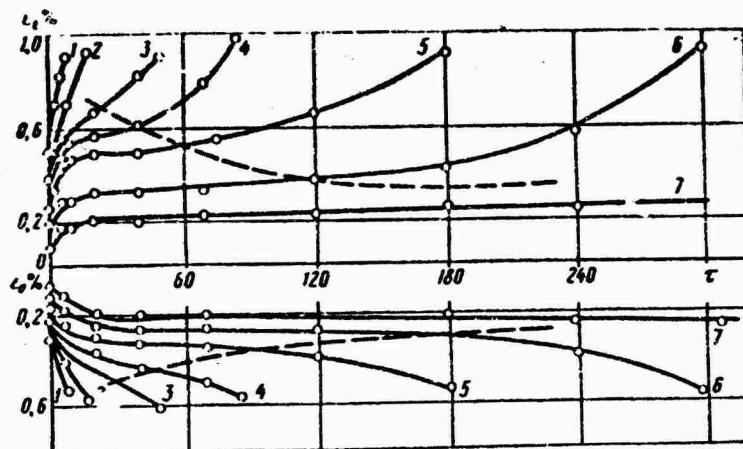


Fig. 63. Creep curves for pipe made of glass-reinforced plastics fabricated by winding glass yarn in 60 plies with a winding angle of  $45^\circ$  C, incorporating polyester binder and tested in water at  $23^\circ$  C  
( $\tau$  in hours)

A крайний	B $\sigma_t$ в $\kappa\Gamma/cm^2$	B $\sigma_0$ в $\kappa\Gamma/cm^2$	A крайний	B $\sigma_t$ в $\kappa\Gamma/cm^2$	B $\sigma_0$ в $\kappa\Gamma/cm^2$
1	220	110	5	55	55
2	165	82.5	6	30	40
3	140	70	7	55	27
4	120	60			

KEY: A — Curve number  
B — in  $\text{kg}/\text{cm}^2$

binder and the breakdown of its adhesive interaction with the glass fiber. Therefore, the foregoing enables us to adopt the transition of the glass-reinforced plastic into the nonmonolithic state as the dangerous stage, and also to regard the moment corresponding to the end of the steady-state creep section as a qualitative transition that must be evaluated as the onset of failure.

Analysis of the creep curves of piping made of glass-reinforced plastics enables us to estimate the hazardousness of relative deformation during creep by the value of the overall deformation accumulated at the moment of the termination of the steady-state creep section  $\epsilon_{II}$ . The creep of the glass-reinforced plastic at an increasing rate resulting from the slow accumulation of high-elastic deformation and crack growth in the binder entails the progressive failure of the latter and the disruption of its interaction with the glass reinforcement. Deformation  $\epsilon_{II}$  is somewhat smaller in absolute value than the maximum deformation. But since  $\epsilon_{II}$  is considerably simpler to determine, by using extrapolation

TABLE 23. VALUES OF THE COEFFICIENTS K, M, AND N

A $\sigma_t$ in $\text{kg}/\text{cm}^2$	B При получении в тангенциальном направлении			C При получении в осевом направлении		
	K	M	N	K	M	N
55	1900	-0,04	262	1000	0,06	-98
110	1100	-0,07	256	700	0,06	-85
165	500	-0,13	249	500	0,08	-75
440	70	-0,16	83	90	0,14	-35

Remark. Principal stresses in the axial direction are equal to half the principal stresses acting in the tangential direction.

KEY: A -- In  $\text{kg}/\text{cm}^2$

B -- For creep in the tangential direction

C -- For creep in the axial direction

methods, it can be employed to estimate the time  $t_{II}$  of the reliable service of piping in specific conditions.

As we can see from Fig. 63, the steady-state creep section for piping made of glass-reinforced plastics is linear. The time  $t_{II}$  in hours corresponding to the end of the steady-state creep section for a specific stress level in the pipe wall can be determined from the following function:

$$t_{II} = \frac{N}{M} - \frac{K}{M} \varepsilon_{II}, \quad (153)$$

where  $\varepsilon_{II}$  is the relative deformation in percent; and

K, M and N are constants for piping with given winding structure and a specific stress level and specific external conditions.

The values of the coefficients in equation (153) for piping made of glass-reinforced plastics fabricated by the helical crossover winding of glass yarn in 20 plies with a winding angle  $45^\circ$  using polyester binder, on exposure to distilled water at  $23^\circ \text{C}$ , are present in Table 23.

Experiments showed that the ratios of these coefficients are associated with the normal stress in the tangential directions  $\sigma_t$  by the following functions:

$$\frac{N}{M} = a\sigma_t^b \quad (154)$$

and

$$\frac{K}{M} = c\sigma_t^d, \quad (155)$$

where  $a$ ,  $b$ ,  $c$ , and  $d$  are constant coefficients determined by the least-squares method from experimental data obtained in short-term tests.

The substitution of the values of  $E/M$  and  $K/M$  from equations (154) and (155) into equation (153) enables us to obtain a relationship to determine the buildup time of overall deformation by the end of the steady-state period for any stress level in pipe walls and, thus, to estimate the period of safe service of piping made of glass-reinforced plastic when subject to long-term loading with internal pressure:

$$t_{II} = a\sigma_i^b - c\sigma_i^d \epsilon_{II}. \quad (156)$$

The constant coefficients have the following values for piping made of glass reinforced plastic fabricated by the method of helical crossover winding at an angle of  $45^\circ$  C using glass yarn in 20 plies and polyester binder for loading with water at  $23^\circ$  C:

$$\begin{aligned} a &= -1.55 \cdot 10^6, & c &= -1.38 \cdot 10^6, \\ b &= 1.3, & d &= 2.47. \end{aligned}$$

Another equation associating time  $t_{II}$  and deformation  $\epsilon_{II}$  directly is the equation of the curve of the end points of the steady-state creep sections for different stress level in pipe walls. Observations showed that this equation corresponds to the following form:

$$t_{II} = f e^{g \epsilon_{II}}, \quad (157)$$

where  $f$  and  $g$  are the constant coefficients determined experimentally during a short time period for large pressures.

Table 24 presents the values of the coefficients  $f$  and  $g$  for piping fabricated by the helical crossover winding of glass yarn at  $45^\circ$  C, for tests made in water at  $23^\circ$  C.

The combined solution of equations (156) and (157) enables us to determine, analytically or graphically, the period of the safe service of piping for a specified internal pressure.

TABLE 24. COEFFICIENTS f AND g

A Метод изготавления труб	B При возможности в тангенциальном направлении	C При возможности в осевом направлении	
		f	g
D Накручен стекловолокна на засыпку смолы:			
E — в 60 слоев	1860	-5,25	126 060
F — в 20 слоев	3310	-2,49	3 950
G Накручен стекловолокна на засыпку смолы в 60 слоях	2190	-5,25	204 000
			26

KEY: A — Method of pipe fabrication  
 B — For creep in the tangential direction  
 C — For creep in the axial direction  
 D — Winding glass yarn incorporating polyester binder  
 E — In 60 plies  
 F — In 20 plies  
 G — Winding glass yarn incorporating epoxy binder in 60 plies

#### Examples of the Calculation of Gas Ducts, Equipment, and Shell Made of Reinforced Plastics

Calculation of ventilation gas ducts by the method of approximations [81]. A gas duct made of glass-reinforced plastic with polyester binder is used to remove hydrochloric acid vapor from vessels. The gas duct-work is fabricated by the method of winding glass yarn on a mandrel. The working pressure in the gas duct is  $1.16 \text{ kg/cm}^2$ . The vapor temperature is  $98^\circ \text{C}$ . The internal duct radius  $r$  is 25.4 cm.

Using the previously obtained experimental data in [81], let us determine the allowable stress. The allowable stress of glass-reinforced plastic at room temperature, with reference to long-term service in air (recommended by the fabricator) [ $\sigma$ ] is  $632 \text{ kg/cm}^2$ . The allowable stress is reduced by 65 percent due to exposure to hydrochloric acid at  $98^\circ \text{C}$ , i.e., it becomes  $224 \text{ kg/cm}^2$ . Owing to mechanical factors (vibration, impacts, and so on), and also for fluctuations in the parameters of the production process, the unknown allowable stress is found to be  $99 \text{ kg/cm}^2$ . The duct wall thickness is determined by formula (144):

$$t = \frac{pr}{[\sigma]e - 0,6p} = \frac{1,75 \cdot 25,4}{99 \cdot 0,8 - 0,6 \cdot 1,75} = 0,57 \text{ cm},$$

where  $p = 1.5 p_w = 1.5 \cdot 1.16 = 1.75 \text{ kg/cm}^2$ ; and

$e = 0.8$  (in the absence of butt joints or with these disregarded,  $e = 1$ ).

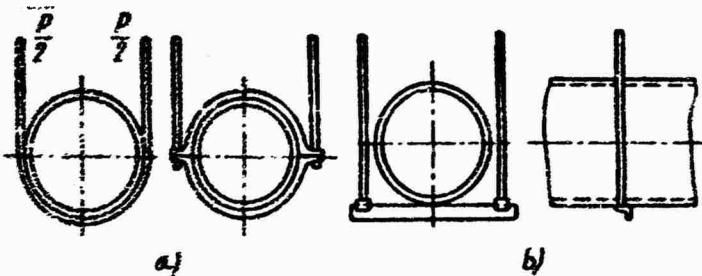


Fig. 64. Suspensions of band (a) and trapezoidal (b) type used in securing pipe made of glass-reinforced plastics



Fig. 65. Cast-on flange

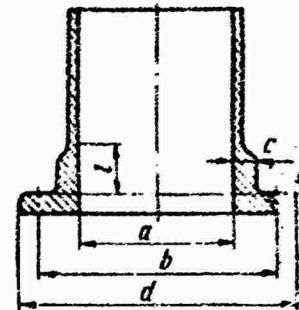


Fig. 66. Monolithic attached flange

Then the effect of suspension fixtures (Fig. 64), which can cause additional stress in the gas duct walls, is checked. The contact angle of the banding with the gas duct  $\beta$  is  $180^\circ$  C for band-type suspension fixtures (Fig. 64 a).

For suspension fixtures with a spacing of 3.048 m and a gas duct diameter of 508 mm, with 1 m of piping weighing 23.8 kg, the total reaction to the suspension banding  $P$  is 71.6 kg.

The stress in the gas duct wall arising due to the action of the suspension fixtures is

$$\sigma_{\max} = \frac{P}{t^2} \ln \left( \frac{r}{t} \right) = \frac{0.01 \cdot 71.6}{0.57^2} \ln \frac{25.4}{0.57} = 6.5 \text{ kg/cm}^2;$$

here the coefficient  $k$  is  $0.02 - 0.0012 (\beta - 90^\circ) = 0.02 - 0.0012 \times (180 - 90) = 0.01$ .

In trapezoidal-type suspension fixtures (Fig. 64 b), point contact with the ductwork is produced. The stress in the wall is checked by the formula

$$\begin{aligned}\sigma'_{2\max} &= - \frac{P}{r^2} \left[ 0.42 \lg \left( \frac{0.215r}{b} \right) + \frac{6}{4\pi} \right] = \\ &= - \frac{71.6}{6.57^2} \left[ 0.42 \lg \frac{0.215 \cdot 25.4}{0.635} + \frac{6}{4 \cdot 3.14} \right] = - 154 \text{ kg/cm}^2,\end{aligned}$$

where  $b$  is the equivalent radius of the contact area ( $b$  is approximately 0.635 cm).

This stress in the wall exceeds the allowable stress ( $99 \text{ kg/cm}^2$ ). Therefore we must increase the number of suspension fixtures or the wall thickness of the gas duct. For a wall thickness  $t = 0.95 \text{ cm}$ ,  $\sigma'_{2\max} = 68.5 \text{ kg/cm}^2$ , i.e., less than the allowable stress.

Then we verify the dimensions of the planar cast-on flange (Fig. 65). The maximum stress in the flange when loaded is determined:

$$\sigma_{\max} = - \frac{3W}{2\pi m t^2} \left[ \frac{2a^2(m+1)}{a^2-d^2} \lg \frac{c}{d} + (m-1) \frac{c^2-d^2}{a^2-d^2} \right].$$

Adopting the following flange dimensions:  $a = 30.95 \text{ cm}$ ,  $d = 25.4 \text{ cm}$ ,  $c = 29.21 \text{ cm}$ , and  $D = 58.5 \text{ cm}$ ; and calculating the effective force from the equation  $W = p (\pi D^2/4)$  ( $W = 4535 \text{ kg}$ ), we obtain the maximum stress  $\sigma_{\max} = -373 \text{ kg/cm}^2$  (the coefficient  $m = 3.3$ ).

This flange is not exposed to a corrosive medium, since it is outside the working space with which the experiment was conducted at  $71^\circ \text{ C}$ . Therefore the stress obtained is beyond the limits of the allowable value. The connecting flange is verified (Fig. 66) based on the new allowable stress, since the working conditions of the flange differ from functioning of the entire gas duct.

Therefore, the allowable stress  $[\sigma] = 632 \text{ kg/cm}^2$  ( $t = 20^\circ \text{ C}$ ) decreases by 29 percent under the effect of temperature. If climatic conditions are also taken into account,  $[\sigma]$  is reduced by 20 percent from its preceding value. Mechanical factors caused a 50 percent reduction in the  $[\sigma]$  value obtained. Finally, with reference to technological parameters (a 10 percent reduction in  $[\sigma]$  from its preceding value) the allowable stress will be  $170 \text{ kg/cm}^2$ .

To determine stresses in the flange, the intermediate parameters  $V_0$  and  $M_0$  are calculated:

$$V_0 = \frac{\frac{f^2 - h^2 T_1}{2t} (l + 0.2325/T_1) p - 2T_2 (k + 0.5377/l) W}{1.86/l + T_1 \left[ k^2 \left( 2 + 0.116 \frac{f}{l} T_1 \right) + 1.6103/k + 0.866/l^2 \right]} = -1.3;$$

$$M_0 = \frac{(h^2 T_1 + 1.86/l) V_0 + h T_2 W - 0.56p \left( f^2 - \frac{h^2}{2t} T_1 \right)}{1.5T_1 h - 3.464l} =$$

$$= 86 \text{ kg} \cdot \text{m/cm}.$$

Here, for  $a = 50.8 \text{ cm}$ ,  $b = 58.42 \text{ cm}$ ,  $d = 61.91 \text{ cm}$ ,  $h = 1.9 \text{ cm}$ ,  $t = 1.9 \text{ cm}$ , and  $f = \sqrt{at} = 9.8 \text{ cm}$ , we have

$$T_1 = \frac{f^2 (3a^2 + 5d^2)}{h^2 (d^2 - a^2)} = 21.5;$$

$$T_2 = \frac{3.58f^2}{h^2 (d^2 - a^2)} \left[ \frac{3}{4} \ln \frac{b}{a} + 0.1 (b^3 - a^3) \right] = 1.854.$$

The longitudinal bending stress in the cylindrical portion that the joint with the flange is

$$\sigma_1' = \frac{6M_0}{t^2} = \frac{6 \cdot 86}{1.9^2} = 143 \text{ kg/cm}^2$$

The total longitudinal stress in the cylindrical portion far from the flange is

$$\sigma_1 = \frac{W}{\pi a \frac{l}{2}} = \frac{4535}{3.14 \cdot 50.8 \frac{1.9}{2}} = 30 \text{ kg/cm}^2$$

The calculated stress will be equal to half  $\sigma_1$ , i.e.,  $15 \text{ kg/cm}^2$ . The maximum longitudinal stress in the piping (at the external surface of the butt section with the flange) is

$$\sigma_1 + \frac{\sigma_1}{2} = 143 + 15 = 158 \text{ kg/cm}^2.$$

The radial stress in the flange is

$$\sigma_1 = \frac{V_0}{h} + p = -\frac{11.3}{1.9} + 1.75 = -4.2 \text{ kg/cm}^2.$$

The bending radial stress in the flange is

$$\sigma_1' = \frac{6}{h^2} \left( M_0 - \frac{1}{2} V_0 h \right) = 160 \text{ kg/cm}^2.$$

The maximum radial stress in the flange (the stress at the external surface at the connection with the cylindrical portion) is

$$\sigma_1 + \sigma_1' = -4.2 + 160 = 155.7 \text{ kg/cm}^2.$$

The tangential stress in the flange is

$$\sigma_2 = \frac{k^2}{4f^3} T_1 (V_0 + hp) = 22.4 \text{ kg/cm}^2.$$

The bending tangential stress in the flange is

$$\begin{aligned} \sigma_2' = \sigma_1' + \frac{0.8}{h^3(d^3-a^3)} & [d^2(-15M_0 + 7.5hV_0) + 1.492W \ln \frac{b}{a}] + \\ & + 0.4475W(b^3 - a^3) = 120 \text{ kg/cm}^2 \end{aligned}$$

The maximum tangential stress in the flange (the stress at the inner surface at the side of the connection with the cylindrical portion) is

$$\sigma_2 + \sigma_2' = 120 + (-22.4) = 97.6 \text{ kg/cm}^2.$$

All calculated stress values are below the allowable value, which is 170 kg/cm<sup>2</sup>.

An example of calculating pressure piping made of glass-reinforced plastic fabricated by winding with the longitudinal-transverse lay-up of the reinforcing material. The internal pipe diameter  $d$  is 50 mm; the internal working hydrostatic pressure in the piping for long-term service  $p_w$  is 40 kg/cm<sup>2</sup>; the piping was fabricated by winding with glass yarn ( $h = 30$  plies) using PN-3 polyester resin. The piping is lined within using polyethylene. Sulfuric acid solution is conveyed around the clock through the piping. The distance between supports on which the pipeline is laid is 3 m. The strength safety margin, with reference to long-term piping service, is 10.

The structural elements of the piping layers are calculated in accordance with the earlier established functions (43) - (66):

The total number of glass yarn laid in the hoop direction per 1 cm segment is

$$N_h = \frac{pd}{2S\varphi n} = 18,$$

where  $p = 10$ ,  $p_w = 400 \text{ kg/cm}^2$ ; and

$f = 2.5 \text{ kg}$  is the breaking force of the glass filament.

For a different  $n$ , the distances between the glass yarn in the same layer  $a_h$  will be as follows:

n . . . . . . .	10	20	30	40	60
a <sub>h</sub> in cm . . . . .	0,06-0,1	0,16-0,2	0,24-0,3	0,32-0,4	0,48-0,6

The number of hoop glass yarn in a single layer for a 1 cm pipe segment is

$$i_h = \frac{1}{a_h} = \frac{1}{0,25} = 4.$$

The number of layers with the hoop winding scheme is

$$M_h = \frac{N_h}{i_h} = \frac{18}{4} = 4,5.$$

We take M<sub>h</sub> = 5.

The total number of glass yarn laid in the axial direction is

$$N_h = \frac{314pd^2 + l^2 (q_1 + q_2)}{400 \cdot \pi d} = 144.$$

The number of longitudinal glass yarns in a single layer is

$$i_{lo} = \frac{\pi d}{a_{lo}} = \frac{3,14 \cdot 5}{0,25} \approx 63,$$

where a<sub>lo</sub> = a<sub>h</sub> = 0.24 - 0.3 cm.

The number of glass yarn layers laid in the axial direction is

$$M_{lo} = \frac{N_h}{i_{lo}} = \frac{144}{63} = 2,29.$$

We take M<sub>lo</sub> = 3.

The width of unidirectional tape consisting of glass yarn simultaneously laid in the hoop direction is as follows for the pitch angle β = 2, 3, and 5°, respectively:

$$B = \pi d \operatorname{tg} \beta_2 = 3,14 \cdot 5 \cdot 0,034 = 0,534 \text{ cm};$$

$$B = \pi d \operatorname{tg} \beta_3 = 3,14 \cdot 5 \cdot 0,05 = 0,784 \text{ cm};$$

$$B = \pi d \operatorname{tg} \beta_5 = 3,14 \cdot 5 \cdot 0,08 = 1,26 \text{ cm}.$$

The wall thickness of piping corresponding to hoop glass yarn layers is

$$t_h = t_g M_h = 0,067 \cdot 5 = 0,33 \text{ cm},$$

where t<sub>h</sub> is the thickness of a single glass yarn layer, taken as 0.067 cm.

The wall thickness corresponding to the longitudinal glass yarn layers is

$$t_{lo} = t_g M_{lo} = 0,067 \cdot 3 = 0,2 \text{ cm}.$$

The total pipe wall thickness is

$$t_{tot} = t_h + t_b = 0.33 + 0.2 = 0.53 \text{ cm.}$$

The experimental verification of the strength of the kinds of piping when subject to short-term loading with internal hydrostatic pressure showed that piping failure occurred at a pressure of  $387 \text{ kg/cm}^2$ , which is close to the calculated value  $p = 400 \text{ kg/cm}^2$ .

Table 25 presents results of calculating the parameters of pressure piping made of glass-reinforced plastics using PN-1 polyester resin fabricated by longitudinal-transverse winding of glass yarn in 10, 20, 30, 40, and 60 plies with an internal diameter of 50 mm for working pressures of 16, 20, 24, 40, and 60  $\text{kg/cm}^2$ ; the strength margin is 10.

Calculation of the strength of pressure piping fabricated by helical crossover winding of glass yarn. The pipe is made of glass yarn in 30 plies with a pitch angle during winding  $\beta_0 = 35^\circ 16'$  using polyester binder. The number of glass yarn layers  $i$  is 8; the glass yarn lay-up density  $m_h$  is  $4 \text{ cm}^{-1}$ ; and the internal pipe diameter  $d$  is 5 cm.

Determine the internal burst hydrostatic pressure for short-term loading.

The calculation is conducted in accordance with formula (93):

$$p_f = \psi \frac{m_h K_f i}{d} [c] = 1.333 \frac{4 \cdot 55.5 \cdot 8}{5} 0.87 = 400 \text{ kg/cm}^2,$$

where  $\psi$  is 1.333 for  $\beta_0 = 35^\circ 16'$ .

Table 26 presents calculated parameters of piping made of glass-reinforced plastics fabricated by helical crossover winding of glass yarn using polyester binder. The number of glass yarn layers was calculated based on function (93) given the condition that the optimal glass yarn pitch angle was  $35^\circ 16'$ . The strength of glass yarn  $K_f$  in the calculations was chosen with reference to its impregnation using polyester binder, i.e., higher than the strength of dry unimpregnated yarn by a factor of 1.6.

The following initial data are used to determine the calculated parameters of piping made of glass-reinforced plastics:

the calculated thickness of a single glass yarn layer, with allowance for the binder, is 0.67 mm;

the lay-up density of glass yarn per cm of length is 5.0 - 6.8 (in 20 plies); 3.3 - 4.0 (in 30 plies); 2.5 - 3.10 (in 40 plies); and 1.67 - 2.10 (in 60 plies); and

the breaking force  $K_f$  of dry glass yarn is chosen based on Table 21.

TABLE 25. WORKING PARAMETERS OF PRESSURE PIPING MADE OF  
GLASS-REINFORCED PLASTICS

Внутреннее рабо- чее статическое давле- ние (рабочее) в кг/см <sup>2</sup>	A	B	C					A	B	C				
			Значение расчетного параметра							Значение расчетного параметра				
			D	E	F	G	H			D	E	F	G	H
			N <sub>h</sub>	i <sub>h</sub>	N <sub>lp</sub>	i <sub>lp</sub>	t <sub>общ</sub> в мм			N <sub>h</sub>	i <sub>h</sub>	N <sub>lp</sub>	i <sub>lp</sub>	t <sub>общ</sub> в мм
16	10	18	2	144	1	2,0		24	40	9	3	68	1	2,7
	20	11	2	88	1	2,0			60	6	3	47	1	2,7
	30	7	2	60	1	2,0								
	40	6	2	46	1	2,0								
	60	4	2	32	1	2,0								
20	10	22	2	164	1	2,0		40	10	44	4	348	2	4,0
	20	14	3	100	1	2,7			20	27	5	214	2	4,7
	30	9	3	68	1	2,7			30	18	5	144	3	5,4
	40	7	3	52	1	2,7			40	14	5	111	3	5,4
	60	5	3	36	1	2,7			60	10	5	76	3	5,4
24	10	26	3	212	1	2,7		60	10	65	6	520	3	6,0
	20	16	3	130	1	2,7			20	40	7	319	4	7,4
	30	11	3	88	1	2,7			30	27	7	215	4	7,4

KEY: A -- Internal hydrostatic pressure (effective value) in kg/cm<sup>2</sup>

B -- Number of filament plies in glass yarn

C -- Value of working parameter

D -- N<sub>h</sub>

E -- i<sub>h</sub>

F -- N<sub>lp</sub>

G -- i<sub>lp</sub>

H -- t<sub>tot</sub>, in mm

Calculation of the ideal cylindrical pressure vessel made of glass-reinforced plastic with a combination scheme of reinforcing material lay-up. The vessel diameter D is 30.5 cm; the effective internal hydrostatic pressure p is 7 kg/cm<sup>2</sup>; the vessel was fabricated by winding hoop and helical ( $\alpha = 30^\circ$ ) fibers; the glass fiber has ultimate rupture strength  $\sigma = 10,500$  kg/cm<sup>2</sup>; and the strength safety reserve is 2.

The required total thickness of the vessel wall is determined based on equation (123), with reference to the fact that for a strength safety margin of 2, the calculated stress in the fibers is

$$\sigma = \frac{10,500}{2} = 5250 \text{ kg/cm}^2;$$

$$t = \frac{3}{4} \cdot \frac{pD}{\sigma} = \frac{3}{4} \cdot \frac{7 \cdot 30.5}{5250} = 0.03 \text{ cm.}$$

TABLE 26. WORKING PARAMETERS OF PRESSURE PIPING MADE OF GLASS-REINFORCED PLASTICS INCORPORATING PN-1 POLYESTER RESIN

Внутреннее гидростатическое давление, кг/см <sup>2</sup> (рабочее)	A	B	C							D						
			Значение параметра i для труб двусторонн в мм							Значение параметра t в мм для труб двусторонн в мм						
			50	70	100	150	200	250	300	50	70	100	150	200	250	300
8	20	2	2	4	4	4	6	6	1,4	1,4	2,7	2,7	2,7	4,0	4,0	4,0
	30	2	2	4	4	6	6	8	1,4	1,4	2,7	2,7	4,0	4,0	5,4	5,4
	40	2	2	4	4	6	6	8	1,4	1,4	2,7	2,7	4,0	4,0	5,4	5,4
	60	2	2	4	4	6	6	8	1,4	1,4	2,7	2,7	4,0	4,0	5,4	5,4
16	20	2	4	4	6	8	10	12	1,4	1,4	2,7	4,0	5,4	6,7	8,0	8,0
	30	2	4	6	8	10	12	14	1,4	1,4	4,0	5,4	6,7	8,0	9,4	9,4
	40	2	4	6	8	10	12	14	1,4	1,4	4,0	5,4	6,7	8,0	9,4	9,4
	60	2	4	6	8	10	12	14	1,4	2,7	4,0	5,4	6,7	8,0	9,4	9,4
24	20	4	4	6	10	12	16	20	2,7	2,7	4,0	6,7	8,0	10,7	13,4	13,4
	30	4	6	8	10	14	18	22	2,7	4,0	5,4	6,7	9,4	12,0	14,7	14,7
	40	4	6	8	10	14	18	22	2,7	4,0	5,4	6,7	9,4	12,0	14,7	14,7
	60	4	6	8	12	14	18	22	2,7	4,0	5,4	8,0	9,4	12,0	14,7	14,7

KEY: A -- Internal hydrostatic pressure (effective value) in kg/cm<sup>2</sup>  
 B -- Number of filament plies in glass yarn  
 C -- Value of parameter i for piping with listed diameter, in mm  
 D -- Value of parameter t in mm for piping with listed diameter, in mm

In the absence of layers with longitudinal fiber lay-up, equation (116) can be represented as  $t_{\alpha} = t - t_h$ . Then the layer thickness corresponding to hoop winding is

$$t_h = \frac{2}{3} t - (t - t_h) \sin^2 \alpha = \frac{2}{3} 0.03 - (0.03 - t_h) 0.5^2; t_h = 0.0167 \text{ cm.}$$

Hence,  $t_{\alpha} = t - t_h = 0.03 - 0.0167 = 0.014 \text{ cm}$ . The same result can be obtained by using equality (128):

$$t_{\alpha} = \frac{2t - 3t_h}{3 \sin^2 \alpha} = \frac{2 \cdot 0.03 - 3 \cdot 0.0167}{3 \cdot 0.25} = 0.014 \text{ cm.}$$

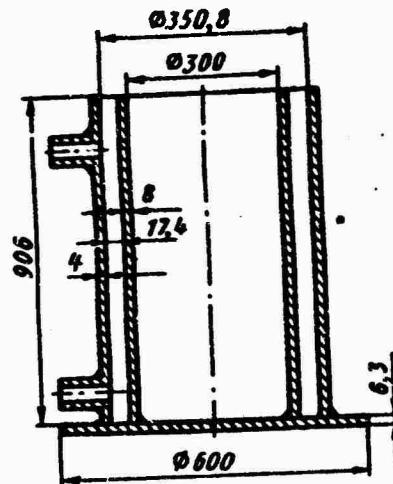


Fig. 67. Reactor with sleeving

Calculation of a reactor with sleeving, based on the method of approximations. The vessel contains a mixture of a hydrochloric acid solution and brine heated with hot water at a pressure of  $300 \text{ kg/cm}^2$ . We must calculate equipment fabricated of polyester glass-reinforced plastic by the winding method (Fig. 67).

Based on the operating conditions of the equipment and the above presented selection of the allowable stress (cf. calculation of ventilation gas ducts), the value of the latter is  $99 \text{ kg/cm}^2$  in the calculation of the internal shell. It was experimentally established that the flexural modulus of elasticity  $E_{be}$  is  $4.9 \cdot 10^4 \text{ kg/cm}^2$  for these conditions. The external shell of the sleeve functions approximately in the same conditions as for the flange of the ventilation gas duct, i.e., the working stress for it can be taken as equal to  $170 \text{ kg/cm}^2$ , and the modulus of elasticity can be taken as  $5.6 \cdot 10^4 \text{ kg/cm}^2$ . The calculation is made by starting from the admissible stress values obtained.

The wall thickness of the sleeve shell is

$$t = \frac{\rho R}{[\sigma_s]} = \frac{3.5 \cdot 17.54}{170} = 0.36 \text{ cm},$$

which is rounded off to 4 mm.

The shell wall thickness of the equipment is determined by referring to the working formula given below:

$$t' = \sqrt[10]{\frac{(\rho')^6 L^4 r^6}{0.807^4 E^4 \left(\frac{1}{1-\mu^2}\right)^3}},$$

where  $p' = 1.5 p = 1.5 \cdot 3.5 = 5.25 \text{ kg/cm}^2$ ;  
 $L = 90 \text{ cm}$  is the vessel height; and  
 $\mu = 0.3$  is Poisson's ratio.

Inserting the corresponding values, we get

$$t' = \sqrt[10]{\frac{5.25^4 \cdot 90^4 \cdot 15^4}{0.807^4 (4.9 \cdot 10^4)^4 \left(\frac{1}{1-0.3^2}\right)^3}} \approx 0.72 \text{ cm.}$$

Calculation of shells made of glass-reinforced plastic by the simplified method given in [70]. It is required to determine the allowable internal pressure for a shell made of glass-reinforced plastic, 200 mm in diameter and with a wall thickness of 3.7 mm, if the ultimate strength of the isotropic technological sample for the given reinforcement and the binder is 90  $\text{kg/mm}^2$ . The ratio of the length of longitudinal and transverse reinforcing layers is 1.2 (i.e.,  $\nu = 2/3$ ).

The strength of the shell wall in the tangential direction is

$$\nu\sigma = \frac{2}{3} 90 = 60 \quad \text{kg/mm}^2.$$

The scale parameter is  $t/r = 3.7/100 = 37 \cdot 10^{-3}$ . Let us turn to the logarithmic plot of strength (cf. Fig. 62). From the point  $37 \cdot 10^{-3}$  we draw a horizontal line until it intersects the curve. From the point of their intersection we drop a perpendicular until it intersects with the line corresponding to the tangential strength of the glass-reinforced plastic,  $\nu\sigma = 60 \text{ kg/mm}^2$ . Then we draw a horizontal to the ordinate axis on which the allowable internal pressures are plotted on a logarithmic scale. The answer obtained ( $300 \text{ kg/cm}^2$ ) corresponds quite accurately due experimental data.

It is required to select material and the coefficient of anisotropy  $\nu$  for a shell made of glass-reinforced plastic if the working pressure is  $240 \text{ kg/cm}^2$ , the internal diameter is 100 mm, and the wall thickness is 3.5 mm. Let us determine the scale parameter:

$$\frac{t}{r} = \frac{3.5}{50} = 70 \cdot 10^{-3}.$$

From the point  $70 \cdot 10^{-3}$ , on the plot (cf. Fig. 62) we draw a horizontal until it intersects the curve and drop a perpendicular from the intersection point. At the same time, we draw a horizontal corresponding to the load  $240 \text{ kg/cm}^2$  until it intersects this perpendicular. The point of their intersection corresponds to the strength of the wall in the tangential direction. We assume  $\nu\sigma = 30 \text{ kg/mm}^2$  with some margin (the margin factor can be taken even higher, depending on the service conditions). This shell is capable of withstanding a pressure of  $270 \text{ kg/cm}^2$ . Knowing that the optimal coefficient of anisotropy  $\nu = 2/3$ , we conclude that the glass-reinforced plastics used in fabricating

shells must have a strength  $\sigma \geq 45 \text{ kg/mm}^2$ . But the use of a shell with  $\nu\sigma = 30 \text{ kg/mm}^2$  and lower would result in a reduction in the allowable pressure or a considerable increase in the shell wall thickness.

These parameters show that the simplified method of calculation enables us to quite accurately solve the main problems confronting designers in designing anisotropic shells made of glass-reinforced plastics with longitudinal-transverse reinforcement scheme.

## CHAPTER FIVE

### TECHNOLOGICAL FEATURES OF THE FABRICATION OF EQUIPMENT AND PIPELINES

#### **Methods of Fabricating Large-Size Articles**

Equipment for the chemical industry made of reinforced plastics can be fabricated by the following methods:

- contact molding;
- press molding;
- sprayup method;
- pressure-bag molding;
- vacuum-injection molding; and
- filament winding.

All technological processes of making articles from glass-reinforced plastics include the operations of impregnating the reinforcing material, direct molding, and curing of the binder.

Contact molding is the simplest of existing methods of making articles from glass-reinforced plastics and is the most widespread and most accessible. Nearly all operations (laying-out, lay-up, impregnation, and machining) are performed manually. The lay-out reinforcing material is placed with layerwise impregnation on molds of any configuration. The molds are made of wood, plaster, metal, and plastic. In making the molds, close attention is given to see that the working surfaces clean and it is often polished. To prevent sticking of the reinforced glass-plastic to the mold, mold-release agents or cellophane are applied. In domestic practice, several film-forming aqueous solutions, as well as solutions of polyvinyl alcohol, acetyl cellulose in acetone, and polyisobutylene and wax in gasoline are used as mold-release agents. The composition of several mold-release agents is given in Table 27 [61].

The mold-release agent based on polyisobutylene is prepared using 2 percent polyisobutylene and 98 percent gasoline; the mold-release agent based on wax consists of 20 percent beeswax and 80 percent gasoline.

TABLE 27. COMPOSITION OF SEPARATING AGENT BASED ON AQUEOUS-ALCOHOLIC SOLUTIONS

A Компоненты	B Содержание компонентов в % для составов		
	I	II	III
Поливиниловый спирт <sup>C</sup>	10	5	5
Этиловый спирт <sup>D</sup>	10	35	40
Глицерин <sup>E</sup>	5	—	—
Вода <sup>F</sup>	75	60	55

KEY: A — Components

B — Content of components in % for the compositions listed

C — Polyvinyl alcohol

D — Ethyl alcohol

E — Glycerin

F — Water

When large-size articles are fabricated (baths, trays, gutters, storage tanks, boxes, hoods, collectors, and tanks), built-up molds can be used with the contact molding method.

Articles in molds can be cured at normal as well as elevated temperatures.

The reinforcing material is impregnated with binder by using brushes, followed by the use of rollers.

When it is not possible to fabricate the entire specimen as a whole using this method, it is fabricated of individually molded parts, which are then cemented.

The contact molding method requires large outlays of manual labor, and the resulting articles are marked by low quality owing to nonuniformity of lay-up of the reinforcing material.

Press molding is the method of fabricating articles on presses under pressure (from 5 to 80 kg/cm<sup>2</sup>) and at elevated temperatures (to 160° C). The pressing is conducted in special metal molds which include a plunger and a die. Sometimes the lay-out reinforcing material is brought together away from the press and is impregnated with binder in advance. More often,

in pressing glass laps (KhZhK and KhZhKh types) are used as the reinforcing material. The curing time depends on the size of the article, its wall thickness, and the pressing temperature. It is 2-5 minutes per mm of wall thickness. Polyester resin, and dry and liquid phenolic resins are used as binders. To avoid warping of an article, it is best that it be cooled in the mold down to 40-50°C. Small containers for storing and conveying corrosive fluids, plates and frames of filter presses, blades of fans and air-cooling equipment, housings for thermal insulation of pipelines, three-ply panels, and glass-reinforced textolite are all prepared by the pressing method.

At the present time molding materials of the premix type are used in our country for molding small- and large-size parts and articles at low and moderate pressures. This material in the form of a paste-like mass consists of polyester binder and chopped fiber from 5 to 25 mm long, and also finely dispersed mineral fillers (kaolin, chalk, and pumice).

The main advantage of molding materials is their relatively long shelf life -- from 2 to 6 months and longer. This material can be pelletized, which is convenient for handling purposes. Impellers of centrifugal pumps, chemically resistant fittings, dampers, bushings, liners, flanges, filter press frames, bearing blocks, plugs, covers, and so on can be made of molding materials.

The sprayup method consists of simultaneously depositing of polyester binder and chopped glass fiber with a pistol-grip sprayer on the mold. The sprayer consists of a pistol-grip sprayer, compressor, and tanks for the resin, initiator, and accelerator.

The pistol-grip sprayer has a mechanism for cutting glass yarn and two nozzles connected with hoses to the compressor and the tanks. Loose glass yarn is used in spraying. When the sprayer is in operation, glass yarn unwinding from bobbins are cut into filaments 20-50 mm long, which are wetted with the binder and sprayed onto the mold. The spraying unit and the mold can be blocked together as part of a flowline. When this is done, the pistol-grip sprayer is automatically moved on a conical path in a closed chamber equipped with forced-draft ventilation, and the mold is rotated. On completion of the spraying process, the sprayed layer is pressed with a rubber diaphragm. Then the mold containing the article is sent to the heat treatment chamber.

The spraying method is used not only in fabricating large-size articles (tanks, baths, and boxes), but also in depositing a layer of anti-corrosion protection on chemical equipment.

By spraying chopped glass fiber without binder added into a perforated mold, uniform-thickness glass fiber blanks of complex configuration can be obtained, which are then sent to be impregnated with binder and to be pressed.

Pressure-bag molding consists in using a single rigid half-mold in fabricating articles, and in employing a rubber bag as the other half-mold; the rubber bag compresses a binder-impregnated stack of reinforcing material by pressure or vacuum. To accelerate the curing process, warm or hot air is fed into the rubber bag. The molding pressure ranges from 1.5 to 4 kg/cm<sup>2</sup>. A polyethylene bag can sometimes be used instead of the rubber bag. Gutters and baths for corrosive liquids, i.e., articles that have curved surfaces of complex configuration, are fabricated by this method.

The filament winding method consists of winding reinforcing material impregnated with a binder on a mandrel with some degree of tension. Heat treatment is carried out on the mandrel in a hot chamber. The cured articles are taken off the mandrel with a winch. Depending on requirements placed on article strength in specific directions, different combinations and modifications of the lay-up schemes are used for reinforcing material on the mandrel during winding.

When the filament winding method is used, articles with increased strength can be obtained, since this method permits the glass fiber to be oriented, which results in maximum effectiveness of its use. When making, for example, cylindrical vessels functioning under pressure where the ratio of the normal tangential stress to the longitudinal stress is 2:1, glass fibers can be arranged so that a vessel is obtained whose strength is twice as great in the hoop direction as in the longitudinal. Thus, by winding, glass fiber is given a predetermined mutual arrangement which ensures the attainment of maximum strength in the required directions. In addition, here the high strength that is exhibited in the glass fibers themselves is utilized. All this makes it possible to obtain extremely high specific strength of plastics compared with metals.

Usually the choice of the winding machine depends on the design of the articles and on the winding mode which must be used in fabricating a given article [4]. There is no universal machine on which all kinds of winding can be carried out. The machine must be large enough so that it can be used in fabricating various articles. At the same time it must be convenient for use in winding with a fairly wide fiber tape in order to reduce the winding time to a minimum.

In building equipment for filament winding, the main requirement is selecting the exact ratio between carriage travel and the number of mandrel revolutions per minute. For example, for hoop winding on a mandrel 3.0 m long with filament tape 6.3 mm wide, 480 revolutions of the mandrel are required per carriage pass. But to execute nearly longitudinal winding on a 1.2-m diameter mandrel for the same tape width 600 passes of the carriage are needed for just a one-layer covering of the mandrel.

In addition, high accuracy in placement of the filament tape is essential, i.e., each subsequent tape must be placed in line with the preceding tape, therefore the ratio between carriage pass and the number of mandrel

revolutions per minute must be properly chosen. The machine must preserve this ratio for the entire winding process without error accumulation. Otherwise, the presence of voids (misses) between tape turns or their overlapping entails lowered quality in the finished article. Another important factor is selecting the required drive for the machine.

A third vital factor is the selection of programming devices. The selection of these devices depends on the complexity of winding configuration, operator qualifications, and the presumed service conditions for the equipment.

There are several kinds of filament winding and different types of filament winding machines [63].

Hoop or radial winding (Fig. 68) permits a high winding angle and complete covering of the mandrel to be accomplished in each carriage pass. The back stroke of the carriage can take place at any time, which does not affect the winding scheme. Simple equipment is required for winding by this method; even a lathe can be used.

Polar winding (Fig. 69) is carried out with a small winding angle. The filament can lie at different distances from the centers at each end. High-speed winding requires a machine with filament fed by an isolating lever. The machine for helical winding with programmed cross feed performs polar winding more slowly.

Helical winding with a broad tape (Fig. 70) affords complete covering of the mandrel in each carriage pass and, just as in the preceding case, can be carried out over individual sections, ensuring local design thickened areas which does not distort the overall winding scheme. This winding method requires simple equipment that affords the choice of an exact ratio of the carriage pass rate to the mandrel rpm. A large mandrel requires a powerful machine and a large number of filament-bearing bobbins.

Helical crossover winding with a narrow tape for a moderate or large winding angle (Fig. 71) requires large number of carriage passes to cover the mandrel. A programming ratio between carriage motion and mandrel revolution is essential. The change in the direction of carriage motion must coincide exactly in time with mandrel revolution. Winding by this method is carried out on the machine for helical winding.

In helical winding with a small pitch angle (Fig. 72), the filament lies around the end of the mandrel in line with the supporting shaft. The winding conditions are the same as for winding with a large angle (cf. Fig. 70). The filament is not stretched and forms a loop during the back stroke of the carriage. During the back stroke of the carriage the filament is grouped so that instead of a tape the filament can form a yarn of circular cross-section. Equipment intended for helical winding with a narrow tape is used for winding by this method. For very small winding angles, cross feed of the carriage is necessary. If this is not used, then



Fig. 68. Circular winding

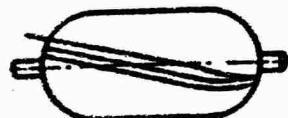


Fig. 69. Polar winding



Fig. 70. Helical winding with wide tape



Fig. 71. Helical crossover winding



Fig. 72. Helical winding at small pitch angle



Fig. 73. Longitudinal winding

a seizing device is used for the unstretched filament. To maintain the tape in a flat position during the carriage back stroke, a programmed rotating eyelet can be used. The action of the device to accelerate mandrel rotation must be programmed exactly with reference to the carriage travel, otherwise the desired filament arrangement will not be maintained. When narrow tapes and winding angles less than  $15^\circ$  are used, the polar-winding machine can be employed.

In longitudinal winding (Fig. 73), the mandrel must remain immobile during the carriage travel time, and then the mandrel must be rotated by exactly  $180^\circ$  while the carriage is at rest. A filament must lie in line with the axis during the mandrel travel time, otherwise the filament will slip. Winding by this method requires exact mandrel positioning. Machines with vertical mandrel are sometimes required to maintain filament uniformity.

The main characteristics of conical winding (Fig. 74) coincide with the characteristics of helical winding, with the exception that the carriage travel must be nonuniform. Programmed nonlinear carriage motion is necessary.



Fig. 74. Conical windings

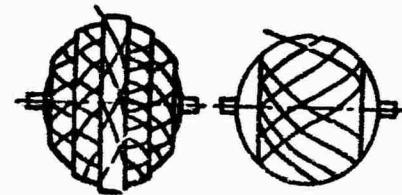


Fig. 75. Simple spherical winding

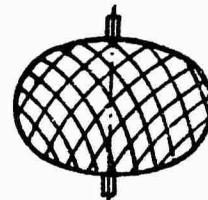


Fig. 76. Simple oval winding

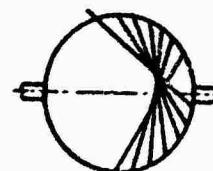


Fig. 77. Strictly spherical winding

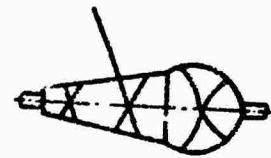


Fig. 78. Combination winding

The remaining requirements on the equipment are the same as those imposed on equipment used in helical winding.

Simple spherical winding (Fig. 75) for a specific winding angle entails the appearance of an excessive number of filaments at the poles. For a more uniform material, winding must be carried out at large angles. In the absence of carriage cross feed, the carriage must be given sinusoidal motion. For small winding angles, cross feed is necessary. If the range of the axis inclination is sufficiently large, a polar-winding machine can be used.

The characteristics of simple oval winding (Fig. 76) coincide with the characteristics of simple spherical winding, with the exception that the carriage travel function or the cross feed pattern differ. For this type of winding, one requires a helical machine with programmed carriage travel or programmed cross feed. A polar winding machine can be used.

For precisely spherical winding (Fig. 77), the filament pass is programmed so as to ensure uniform wall thickness and uniform strength over all sections of the sphere. It is best to use a special machine for this kind of winding. In some cases, the complex winding of all helical-winding machine motions is necessary.

Combination winding (Fig. 78) must be conducted by hand. Here there must be no side slippage of filament from the mandrel surface. In order to

carry out winding of this kind with a machine, the machine must reproduce the motions of hand winding. Programmed motions in several axes can be required.

The most common kind of machine is the machine for helical winding. The mandrel is positioned horizontally on this machine. The carriage located on the machine has a reciprocating motion parallel to the longitudinal axis of the mandrel.

The mandrel is usually positioned vertically on machines intended for polar winding and a rotary lever lays the filament in the polar direction, nearly parallel to the long axis of the mandrel. These two kinds of machines are used most frequently.

The winding method is of considerable interest for chemical machine building, since most technological equipment has the form of bodies of revolution. Piping that is intended for technological and ventilation purposes, reactors, storage tanks, cisterns, tanks, flues, scrubbers, absorbers, and so on are fabricated by the winding method from glass-reinforced plastic for the chemical industry. At the present time use is made of winding equipment for making articles of glass-reinforced plastic up to 5 m in diameter and up to 16 m long. Automatic control of the winding process is provided using programmed regulation of the lay-up scheme for the reinforcing material.

In molding by the vacuum-injection method, prelaid-cut reinforcing material is placed in a build-up mold, which is then hermetically closed. Glass lap is most often used as the reinforcing material. The reinforcing material is impregnated with binder using a vacuum system that simultaneously evacuates the air. After impregnation, the mold is heated to 60-70° C and the binder undergoes polymerization. A composition consisting of one part by weight TGM-3 polyester acrylate resin and three parts by weight TMGF-11 polyester acrylate resin is used as the binder.

#### Choice of Starting Material

Depending on the strength requirements of articles made of glass-reinforced plastics, the method of their fabrication, and the conditions of their service, fabric or nonfabric materials, or continuous filament can be used as the reinforcing materials in the fabrication of chemical equipment and pipelines.

Most often used of fabric materials are the glass cloth types ASTT (b) S<sub>2</sub>, TS-8/2-250, STS-41, and TU-16/13. They are made of twisted filaments consisting of continuous fiber of alumina borosilicate composition glass using various sizers. These are used as reinforcing materials in structural glass-reinforced plastics prepared on the basis of polyester, epoxy, and epoxy phenolic resins. A paraffin-emulsion sizer is used for the fabric types ASTT (b)-S<sub>2</sub>, TS-8/3-250, and TU-16/13; and grade A-41 waterproofing adhesive sizer -- for STS-41 type cloth. The characteristics of these glass cloth types are given in Table 28.

TABLE 28. CHARACTERISTICS OF GLASS CLOTH OF VARIOUS GRADES

A Показатели	B Значения показателей для стеклотканей марок			
	C ASTT(b)-C <sub>2</sub>	D TS-8/3-250	E STS-41	F TU-16/13
G Ширина ткани в см	70; 90; 100	92±2	92±2	70; 80; 90
H Масса 1 м <sup>2</sup> в г	380—400	290±7	360±25	308±12
I Толщина в мм	0,3	0,23±0,02	0,3	0,27±0,03
J Разрывная нагрузка полоски ткани размером 25×100 мм в кг: по основе по утку	≥275 ≥162	≥255 ≥145	≥265 ≥145	≥170 ≥140
K Диаметр волокна в мкм	6—8	5—7	8—9	5—7

KEY: A -- Indicator

B -- Value of indicators for glass cloth of listed grades

C -- ASTT(b)-C<sub>2</sub>

D -- TS-8/3-250

E -- STS-41

F -- TU-16/13

G -- Width of cloth in cm

H -- Weight of 1 m<sup>2</sup> in grams

I -- Thickness in mm

J -- Breaking load of cloth strip 25 x 100 mm in kg:

for base

for weft

K -- Fiber diameter in microns

Roving fabric of the types TZhS-0.7 and TZhSK-0.5 (Table 29) are produced by linen interweaving from rovings of alumina borosilicate-composition glass with fiber diameter 9-11 microns. They are intended for the fabrication of high-strength glass-reinforced plastics by the contact molding method (TZhS-0.7) or by winding (TZhS-0.5).

A glass roving is an untwisted yarn prepared from a large number of continuous primary glass filaments (60 or 30) 42 tex in thickness. Rovings are prepared from filaments consisting each of 200 elementary fibers of alumina borosilicate glass; the diameter of the elementary fiber is 9-11 microns.

TABLE 29. CHARACTERISTICS OF ROVING FABRIC OF DIFFERENT GRADES

1 Показатель	2 Значения показателей для тканей марок	
	3 ТЖС-0.7	4 ТЖСК-0.5
5 Ширина ткани в см	80±2; 100±2	90±2; 100±2
6 Толщина в мм	0,7±0,1	0,5
7 Масса 1 м <sup>2</sup> в г	≤900	≤625
8 Разрывная нагрузка полоски ткани размером 25×100 мм в кг:		
9 по основе	≥250	>550
10 по утку	≥300	≥60

KEY: 1 -- Indicator  
 2 -- Value of indicators for cloth of grades listed  
 3 -- TZhS-0.7  
 4 -- TZhSK-0.5  
 5 -- Width of cloth in cm  
 6 -- Thickness in mm  
 7 -- Weight of 1 m<sup>2</sup> in gram  
 8 -- Breaking load of cloth strip 25 x 100 mm in size,  
       in kg  
 9 -- for base  
 10 -- for weft

Type ZhN 10-42 x 30-289 winding glass roving is finished by using No 289 sizer and is intended for the fabrication of glass-reinforced articles by the winding method (piping, cylinders, shells, tanks, equipment, and so on) and by the drawing method (rods, cables, gratings, profiles, and so on) based on polyester resins.

Loose rovings of the types ZhSR-60 (3) and ZhR10-42 x 60-28 are finished using the sizers No 3 and No 28, respectively. Stiff laps are made from ZhSR-6 (3) roving. ZhR10-42 x 60-28 roving is used in making articles from glass-reinforced plastics with increased light transparency (~ 80 percent).

Characteristics of glass rovings are presented in Table 30.

Lap made of chopped glass filaments of the types KhZhK-400-G-S, KhZhK-600-G-S, and KhMK-1200-A-41 are roll materials consisting of segments of glass filament 50 mm long randomly arranged in the horizontal plane and held together with an aqueous solution of the S-230 dispersant (KhZhK-400-G-S and KhZhK-600-G-S) or by sewing to a backing material (KhMK-1200-A-41). Primary glass filament is prepared using No 3 or A-41 sizers.

The lap is used in fabricating articles made of glass-reinforced plastics by the methods of contact and vacuum molding (KhZhK-400-G-S and

TABLE 30. CHARACTERISTICS OF GLASS ROVINGS

1 Показатели	2 Значения показателей для стеклоргутов марок		
	3 ZhN10-42x30-289	4 ZhSR-60 (3)	5 ZhR10-42x60-28
6 Разрывная нагрузка в кг	≥30	≥70	≥70
7 Число первичных нитей в жгуте	30	60	60
8 Толщина жгута в текс	1250	2500	2500
9 Вид (марка) замасливателя	№ 289	№ 3	№ 28
10 Содержание замасливателя в %	1,0	1—1,2	1—1,2
11 Содержание влаги в %	≤0,5	≤0,1	≤0,1

- KEY:
- 1 --- Indicator
  - 2 --- Value of indicators for glass roving grades listed
  - 3 --- ZhN10-42x30-289
  - 4 --- ZhSR-60 (3)
  - 5 --- ZhR10-42x60-28
  - 6 --- Breaking load in kg
  - 7 --- Number of primary filaments in roving
  - 8 --- Thickness of roving in tex
  - 9 --- Kind (grade) of sizer
  - 10 --- Content of sizer in %
  - 11 --- Moisture content in %

TABLE 31. CHARACTERISTICS OF GLASS LAP

1 Показатели	2 Значения показателей для холстов марок		
	3 XZhK-400-G-S	4 XZhK-600-G-S	5 XMK-1200-A-41
6 Ширина в см	90; 125; 160	90; 125; 160	90
7 Масса 1 м <sup>2</sup> в г	400±50	600±50	1200±100
8 Толщина в мм	1±0,2	1,8±0,2	3,0
9 Содержание связки для склеивания нитей в %	5,0±1,0	5,0±1,0	—

- KEY:
- 1 --- Indicator
  - 2 --- Value of indicators for lap of grades listed
  - 3 --- XZhK-400-G-S
  - 4 --- XZhK-600-G-S
  - 5 --- XMK-1200-A-41
  - 6 --- Width in cm
  - 7 --- Weight of 1 m<sup>2</sup> in grams
  - 8 --- Thickness in mm
  - 9 --- Content of binder for cementing filaments in %

b7

KhZhK-600-G-S) or by the methods of press and contact molding (KhMK-1200-A-41) based on polyester maleic and polyester acrylate resins.

Characteristics of glass lap are given in Table 31.

KhZhKN type lap composed of continuous glass filaments of alumina borosilicate composition consists of roll material of continuous glass filament with fiber diameter to 16 microns arranged as groups of eight of different size and held together with a binder — polyvinyl acetate emulsion. Lap is used in making flat and roll glass-reinforced plastics by the press molding method using phenol-formaldehyde resins. The lap width is  $\leq 1400$  mm, the weight of 1 m<sup>2</sup> is  $300 \pm 50$  g, and the binder content is 2-3 percent.

#### Use of Combinations of Reinforced Plastics and Other Materials in Making Equipment

The use of laminated plastics in chemical equipment making is sometimes limited by their inadequate chemical resistance and gas-tightness. Producing high-strength gas-tight and chemically resistant glass-reinforced plastics for chemical equipment is one of the fundamental problems. We know that the first efforts in this direction were undertaken by foreign companies in the building of tanks up to 14 m<sup>3</sup> in capacity. In fabricating a tank, binder is placed in the mold in a gel-like state forming upon curing a homogeneous protective layer 1.6 mm thick which ensures the gas-tightness of the vessel under specific service conditions [23]. From a study of combined copolymerization of elastomeric materials, for example thiokol and epoxy resins, a rubber type protective layer was obtained. These combinations are somewhat superior in chemical resistance to binders and in addition at normal temperature ensure the required gas-tightness of articles. But at elevated temperatures and loads defects appear in the protective layer in the form of cracks.

Rubber is an effective protective material for glass-reinforced plastics in chemical equipment building. Rubber is used in combination with the glass-reinforced plastic at the article-molding stage or to line molded articles. In the United Kingdom, the FRG, and the United States [93] methods of protecting glass-reinforced plastics vessels with soft polyvinyl chloride after cementing it to the internal surface of the equipment are employed. This kind of tank is intended for transporting corrosive liquids, for example, hydrochloric acid.

Also employed are combinations of glass-reinforced plastics with metals (seamless steel and titanium) in making piping and equipment. High strength, gas-tightness, and chemical resistance of articles is achieved in these applications, with the simultaneous reduction in the consumption of special short-supply metals [19]. However, building and using chemical equipment made of glass-reinforced plastics with metal liner involves a number of difficulties. They include the difficulty of welding when the equipment is repaired, the additional temperature stresses and defects

arising owing to the considerable difference in the coefficients of linear expansion when vessels are used at elevated temperatures, and so on.

The most promising plastics used in combination with glass-reinforced plastics in making chemical equipment is stiff polyvinyl chloride and polyethylene. These plastics are chemically resistant in most corrosive media at 40-70° C and ensure the gas-tightness of articles. The technology of fabricating equipment from glass-reinforced plastics in combination with thin-sheet polyvinyl chloride involves the following:

fabricating equipment components (shell, bottom, and connecting piece) of polyvinyl chloride;

strengthening fabricated elements with the glass-reinforced plastic; and

assembly of equipment components using welding and cementing.

To increase the bonding of the glass-reinforced plastic to polyvinyl chloride, the surface of the latter is degreased with dichloroethane and covered with a thin layer of perchlorovinyl cement, after which glass cloth is applied, which is then strengthened with the glass-reinforced plastic to the required thickness.

When large-size equipment is made of glass-reinforced plastics in combination with ethylene, semifinished articles made of glass cloth with a 2-2.5 mm thick polyethylene sheet molded or rolled during the extrusion process are used.

The intermediate glass-fiber material bonding the cladding thermosetting plastic with the glass-reinforced plastic can be made in several ways. To do this, doubled materials consisting of a layer of the cladding thermosetting plastic and the glass-fiber material, glass cloth, or glass mat securely bonded to it are prepared. For thermosetting plastics that are easily melted and welded, but which are difficult to cement, the method of periodic and continuous molding is used, and the cementing method is used for readily cementable thermosetting plastics.

The pressing method makes it possible to achieve higher bonding strength of the thermosetting plastic with the glass-fiber material; it is more technologically sound, does not require the use of cement, and the resulting material with a higher temperature compared with cemented unions. Essentially, the pressing methods consist of molten or softened thermosetting plastic diffusing under pressure into the glass fiber material and being fixed in it after some temperature reduction.

The periodic pressing method is carried out on hydraulic multi-level presses equipped with heaters. The continuous pressing method can be carried out with existing extruders supplemented with the attachment of devices for feeding and heat-treating glass fiber materials.

Of major interest in chemical equipment making is the combination of glass-reinforced plastics with polytetrafluoroethylene and polypropylene [64].

## Fundamental Principles in Safety Techniques, Industrial Hygiene, and Fire Prevention

Enterprises making chemical equipment and piping using glass-reinforced plastics based on PN-1 type polyester resins are classified as dangerous and fire-hazardous production facilities by the nature of the starting materials processed. Special instructions on safety measures, industrial hygiene, and fire prevention have been developed to ensure personnel safety.

The main toxic and fire-hazardous components in the production of chemical equipment and pipelines made of glass-reinforced plastics are the styrene polyester resins, initiators (peroxide compounds), organometallic accelerators, epoxy resins, and amines and anhydrides used as curing agents.

Organic peroxides are used as initiators in the curing of polyester resins. When a peroxide is added to a resin in excess during the heat-treatment process, the curing reaction takes place rapidly, which can lead to combustion. In cold-curing glass-reinforced plastics, in addition to the initiator, to the resin is added an accelerator, for example, cobalt naphthenate, but after it has been already well blended with the peroxide. When cobalt naphthenate is blended directly with the peroxide an explosion can take place, since the peroxide decomposes vigorously, giving off large amounts of heat. Therefore careful attention must be given to see that the accelerator is not added to the resin before the initiator has been well blended with it.

Organometallic accelerators can be stored for an indefinitely long time. But peroxides gradually decompose even at room temperature and lose their activity. They must be stored far from sources of heat, preferably in small amounts in the cold. But if this type of storage is not possible, peroxides must be stored far from work stations.

In making articles from polyester glass-reinforced plastics, the following components are fire- and explosion-hazardous.

Styrene is a readily flammable liquid with a flash point of 31° C. Styrene vapor in air forms explosive-dangerous mixtures (when the styrene content is in the limits 0.1-1.6 percent by volume at atmospheric pressure and 29.3-65.3° C). Usually solutions of polyester resin in styrene are used. Styrene vapors were not be given off near an open flame, heating elements, or heated equipment. Styrene vapor is toxic. It exhibits irritating properties, and its maximum allowable concentration in air must not exceed 0.05 mg/l.

Polyester resin and cobalt naphthenate (accelerator) are explosion-hazardous owing to their content of styrene (up to 33 percent in the resin and up to 90 percent in the accelerator). It is recommended to take the same precautionary measures as for the handling of styrene. Unsaturated polyester resin must be stored at temperatures from 0 to +5° C. The storage schedule at +20° C is 2 months. The resin is handled as a fire-

hazardous product in heavy iron drums 100 and 250 liters in capacity. The internal surfaces of the drums are protected, washed, and dried. The plug liners are made of rubber or lead.

Benzoyl peroxide causes a flash followed by explosion when heated about 40-60° C, when struck or subject to friction, and also in contact with mineral acids, dimethyl aniline, or tertiary aromatic amines. Before use small portions of benzoyl peroxide are dried on filter paper at room temperature. To avoid explosion, benzoyl peroxide must not be rubbed. It is stored in glass bottles under a layer of water or alcohol.

Isopropylbenzene hydroperoxide (giperiz) is an explosive, flammable, and toxic brown liquid. When in contact with cobalt naphthenate, siccative, rubber, lead, mineral acids, hot, and easily flammable substances it explodes. As a rule, isopropylbenzene hydroperoxide is stored in the dark.

With reference to the toxicity of components, all production operations involving polyester resins are carried out with effective forced-draft ventilation. Rubber gloves and special creams and pastes based on methyl cellulose and casein are used to protect the hands.

Glass dust produced in the machining of glass-reinforced plastics is also dangerous, therefore its maximum allowable concentration is 3 mg/l. Water or oil cooling of the cutting tool is used in the machining of glass-reinforced plastics.

Epoxy resins have also found wide use in the fabrication of chemically resistant articles made of glass-reinforced plastics. The Ministry of Public Health of the USSR, with the participation of the Institute of Industrial Hygiene and Occupational Diseases, drew up sanitary regulations for working with epoxy resins. These regulations are mandatory also in production facilities involving epoxy glass-reinforced plastics.

In working with epoxy resins, the following are widely used as curing agents: organic and inorganic acids and their anhydrides (phthalic and maleic), and also aliphatic and aromatic amines (ethylene diamine, hexamethylene diamine, polyethylene polyamine, and so on). We know that amine type curing agents are toxic [52, 53]. Symptoms of intoxication include the appearance of patches at the sites of contact with reagents, followed by reddening turning to folliculitis. A strong reaction to the disease is usually manifested near the eyes. General symptoms include headaches, dizziness, and fatigue accompanied by gastrointestinal disorders, followed by vision disorders. In very mild cases emollients can help. In all cases of dermatitis, medical help is mandatory.

The danger of dermatitis caused by amines can be reduced by the following:

using good ventilation ensuring the removal of all volatiles;  
not allowing large amounts of the toxic substances exceeding the current production requirement to be present at a work station;

preventing possible direct contact with the substance by using protective creams, and, if necessary, protective clothing and protective gloves. Washing must be done using only water and soap; the use of solvents in washing (acetone or dichloroethane) is forbidden, since they cause cracking of skin;

making mandatory the safest method of handling these substances and providing required training and instruction of workers; and

providing as far as possible the measuring out, blending, and distributing of materials with automatic gas-tight devices.

Operation such as heating of epoxy resin and preparing its blends with curing agents are unfavorable from the hygienic standpoint. When epoxy resin is blended with curing agents, volatile toxic substances are given off, which makes it necessary to have multiple air changes in the working quarters.

When epoxy resins are heated to 60° C, volatile substances are given off, whose composition includes epichlorohydrin and toluene. The largest quantity of epichlorohydrin vapor is given off from ED-5 epoxy resin, and the largest compound of toluene vapors given off by E-40 resin; the higher the resin temperature, the more volatiles that are given off. These volatiles exhibit toxic action on the nervous system and the liver. For this reason, maximum allowable standards for the vapor concentration of volatiles are specified.

In addition to hygienic requirements, sanitary regulations also establish requirements on technological processes and equipment intended for processing epoxy resins and glass-reinforced plastics based thereon.

#### Quality Control

Fabricating reinforced plastics and equipment made therefrom is carried out mainly simultaneously, therefore physicomechanical properties of the material can be checked only after articles have been built.

Defects of the material in articles can be divided into external and internal. External defects (unevenness of surface layer, flaws and cracks in it, and the exposure of the glass fiber texture at the surface) only slightly affect the mechanical properties of the material in the initial period of service, but they must be eliminated, since subsequently they promote the penetration of corrosive media into the reinforcing material.

Internal defects (exfoliation, porosity, cracks, flaws, deviations in the resin/fiber ratio, and so on) significantly affect the mechanical properties of the glass-reinforced plastic, especially, for work under load.

The quality of the material in chemical equipment and pipelines made of reinforced plastics and their unions is checked successfully in four stages:

a check on the quality of the initial components in the composition; monitoring of the observance of the technological process in article fabrication;

monitoring of material quality in finished articles and unions; and determination of the basic physicomechanical characteristics of the material and unions.

Monitoring the quality of the starting materials involves analyzing the binder (determining viscosity, gel formation time, and isotherm maximum), analyzing curing additives, and checking the quality of the reinforcing material (moisture content).

Monitoring observance of the correctness of the technological process is done operation by operation, including the determination of temperature and humidity in the working area, curing time of articles, consumption of binder and reinforcing material, and also the correctness of the preparation of rigging, accessories, and the carrying out of technological operations.

The quality of material in finished equipment and piping made of reinforced plastic is checked by the following methods:

an internal inspection is made of finished articles;  
the nature and dimensions of internal defects are uncovered using monitoring equipment;  
the wall thickness of the article is measured; and  
physicomechanical characteristics of the material is determined on specimens cut from articles.

Special equipment is available for finding internal defects [60]. Defects in a material at a depth of not more than 6 mm are determined with the DIK-1 impedance flaw detector that permits monitoring from the most accessible side in an article. Using this device, air inclusions and exfoliation covering an area of not less than  $20 \text{ mm}^2$  are revealed in glass-reinforced plastics and unions, and the boundaries of defects are also determined. The monitoring method consists in moving the transducer over the surface of the equipment and watching the signal lamp. If when the transducer is being moved the signal lamp goes on, this means that a defect has been detected.

Defects lying at depth from 4 to 30 mm are discovered and estimated using the DUK-12 ultrasonic flaw detector, that permits monitoring with access to the article from one side. The instrument makes it possible to measure the thickness of a glass-reinforced plastic article to 30 mm. The boundaries of air inclusions and exfoliations are determined with this instrument and their depth is ascertained. The minimum area of a defect that can be determined with this instrument is  $20 \text{ mm}^2$ .

The wall thickness of equipment and piping is measured with universal measuring devices and feeler gauges. To make measurements of the wall

thickness at sites located far from edges and that are inaccessible to measurement with an ordinary measuring device, the TPM-1 instrument is used that permits measurement of wall thickness to a precision of up to  $\pm 5$  percent within the measurement range 0-20 and 20-40 mm.

Physicomechanical properties of material in an article are determined to verify their correspondence with calculated values. Specimens for these tests are cut from articles or special allowances on articles. Here determinations are made of the ultimate tensile strength, the ultimate static bending strength, the tensile modulus of elasticity, density, percent content of reinforcing material and binder, and water absorption, and a qualitative and quantitative microstructural analysis is made. The qualitative microstructural analysis can be made using series-produced equipment, FMM-2 model instruments that permit a magnification in transmitted and reflected light from 0.5 to 20.

## CHAPTER SIX

### PIPING, EQUIPMENT, AND PIPELINES

#### Technical and Operating Characteristics of Piping Made of Glass-Reinforced Plastics

Operating characteristics of piping made of reinforced plastics depend heavily on the type of binder, pipe and orientation of reinforcing material, kind of primary-glass filament sizer ensuring adhesive bonding of the binder and the fiber, and also the kind of material used in the gas-tight coating.

Experience shows that glass-reinforced plastic piping based on glass roving with "paraffin emulsion" sizer without the use of an internal gas-tight coating malfunctions owing to a breakdown in gas-tightness. The breakdown in gas-tightness shows up by liquid penetrating into existing and forming pores and cracks of the heterogeneous material of the piping under the effect of loading, and the liquid penetrates the surface in the form of small drops, that is, the piping as it were "sweats". Later, the "sweating" is transformed into profuse effusion of drops. The cause of this phenomenon has not yet been adequately studied. It was established [41] that the nature of the binder, its curing regime, and the orientation of the reinforcing material in pipe fabrication affect gas-tightness. Since upon a breakdown in gas-tightness cracks and irreversible type defects appear in the binder and grow larger, the maximum state for piping as to gas-tightness can be regarded as the initiation in piping walls of cracks and defects of critical size. In this case the bearing capacity of piping will be determined by the loads corresponding to the limiting state of piping as to gas-tightness.

Piping made of glass-reinforced plastics produced without internal protection [4] can be used at working pressures to 4-6 kg/cm<sup>2</sup>. The array of these pipe types is shown in Table 32.

The time nature of the breakdown of gas-tightness of unprotected pipe made of glass-reinforced plastics has been confirmed by a test made of piping fabricated by helical crossover winding with glass roving in

TABLE 32. RANGE OF GLASS-REINFORCED PLASTIC PIPE FABRICATED WITHOUT INTERNAL SEALANT

1 Внутренний диаметр в мм	2 Наружный диаметр в мм	3 Толщина стенки в мм	1 Внутренний диаметр в мм	2 Наружный диаметр в мм	3 Толщина стенки в мм
50-1.0	60	5	100-1.25	110	5
	70	10		120	10
	80	15			
60-1.0			125-1.5	135	5
	72	5		145	10
	80	9	150-2.0	160	5
80-1.0	90	14		170	10
			300-3.0	310	5
	100	10		320	10

Remarks: 1. Pipe length is  $6 \pm 0.5$  m (pipes 9-12 m long can be manufactured on special order).

2. Wall thickness deviation is allowed within the limits  $\pm 1$  mm.

KEY: 1 -- Inner diameter in mm

2 -- Outer diameter in mm

3 -- Wall thickness in mm

TABLE 33. SERVICE LIFE OF PIPING MADE OF GLASS-REINFORCED PLASTICS WITHOUT INTERNAL SEALANT WHEN EXPOSED TO HYDROSTATIC PRESSURE

1 Примыкающее напряжение в тангенциальном направлении в кг/см <sup>2</sup>	2 Время до нарушения герметичности в ч при температуре среды в °C		
	23	35	45
1200-1300	10-8	2-1	0.8-0.6
900-1000	80-50	15-9	4.5-2.5
600-700	800-500	90-60	25-15
200-300	10 000-8000	1000-700	250-150

KEY: 1 -- Normal stress in tangential direction, in kg/cm<sup>2</sup>

2 -- Time to failure of gas-tightness in hours at temperature of medium listed, in °C

60 plies with a winding angle of  $54^{\circ} 44'$  using PH-1 polyester binder [18]. For short-term loading with internal hydrostatic pressure, the breakdown of gas-tightness of an experimental batch of pipes took place at normal stress values in the tangential direction  $\sigma_t = 1600 - 2000 \text{ kg/cm}^2$ . The life expectancy of piping with long-term loading using water is shown in Table 33.

Experiments show that when there is a breakdown in gas-tightness, the mechanical strength of glass-reinforced plastics remains quite high. Therefore when a protective gas-tight coating is present, the existing strength margin of the piping material permits, in spite of the presence of the microdefects, a preservation of the bearing capacity of piping for relatively long time periods.

Glass-reinforced piping with gas-tight layer made of high-pressure polyethylene is also produced. The pipe length is up to 6 m. The strength margin with reference to long-term service at temperatures from -50 to +60° C is 10. The piping is intended for conveying chemically corrosive media to which high-pressure polyethylene is resistant, at working pressures of 6 and 16  $\text{kg/cm}^2$ .

Physicomechanical characteristics of polyester glass-reinforced plastic (the material used in this piping) are as follows:

Rupture stress in $\text{kg/cm}^2$ in tension:	
in the tangential direction	2500 - 3500
in the axial direction	1250 - 1750
Modulus of elasticity in $\text{kg/cm}^2$ in tension:	
in the tangential direction	$1.5 \cdot 10^5 - 2 \cdot 10^5$
in the axial direction	$0.7 \cdot 10^5 - 1 \cdot 10^5$
Relative temperature coefficient of linear expansion in $\text{deg}^{-1}$	$10 \cdot 10^{-6} - 25 \cdot 10^{-6}$
Coefficient of thermal conductivity in $\text{kcal}/(\text{m} \cdot \text{hr} \cdot \text{deg})$	0.2 - 0.3

Pipes are connected into a pipeline using monolithic glass-reinforced plastic flanges molded of AG-4S molding compound, and flanges are cemented at the pipe ends.

The most favorable condition for reliable service life of piping fabricated by helical crossover winding of glass roving is exposure only to internal working pressure without the application of additional bending moments. Therefore a pipeline assembled of pipes of this type must be placed on an increased number of supports or in gutters.

Biplastic pipes (glass-reinforced plastic-thermosetting plastic) are presently fabricated by longitudinal-transverse winding with glass

yarn in 30 plies using PW-1 polyester binder. Thin-walled piping in the light series made of high-density polyethylene is used as the gas-tight layer.

The pipes are intended for transporting corrosive media to which high-density polyethylene is stable at temperatures from -50 to +60° C. The strength margin of glass-reinforced plastic with reference to long-term pipe service is 10. An advantage of this type of pipe is its capacity to take additional bending moments, which makes it possible to use a smaller number of supports and brackets in pipeline installation.

Mechanical properties of biplastic pipes are as follows:

Short-term strength of pipe in  $\text{kg}/\text{cm}^2$  in tension:

in the tangential direction	3000 - 4000
in the axial direction	1500 - 2000

Modulus of elasticity in  $\text{kg}/\text{cm}^2$  in tension:

in the tangential direction	$150 \cdot 10^3 - 250 \cdot 10^3$
in the axial direction	$75 \cdot 10^3 - 125 \cdot 10^3$

To estimate their efficiency in service conditions, biplastic piping was subject to long-term tests to failure using combined exposure to internal hydrostatic pressure, corrosive medium, and increased temperatures. Tests results are represented by longevity curves in logarithmic coordinates (Fig. 79). The longevity curves (1, 2, 3) were plotted for biplastic piping with internal diameter of 44 mm, total wall thickness 4.5-5 mm, and 2 mm-thick gas-tight layer.

Using the extrapolation of longevity curves shown in Fig. 79, we can determine without reference to the aging of the material the assumed longevity of biplastic piping for relatively moderate loads. For example, the assumed longevity of biplastic piping when exposed to internal hydrostatic pressure produced by water at 20-22° C is one year at a pressure of  $40 \text{ kg}/\text{cm}^2$ , 3.5 years at  $30 \text{ kg}/\text{cm}^2$ , 7 years at  $25 \text{ kg}/\text{cm}^2$ , and 19 years at  $20 \text{ kg}/\text{cm}^2$ .

At a 60° C water temperature, the assumed longevity is 1 year at a pressure of  $15 \text{ kg}/\text{cm}^2$ , 7 years at  $10 \text{ kg}/\text{cm}^2$ , 11.5 years at  $9 \text{ kg}/\text{cm}^2$ , and 23 years at  $8 \text{ kg}/\text{cm}^2$ .

Tests showed that at water temperature of 80° C the longevity of biplastic piping is 3 times lower than at 60° C.

Long-term static strength of biplastic pipes is strongly affected by the action of moisture at their external surface. For example, the assumed longevity of pipes subject to external exposure to water at 20-22° C is as follows: 7 months for a pressure of  $20 \text{ kg}/\text{cm}^2$ , 1.3 years at  $15 \text{ kg}/\text{cm}^2$ , 3.5 years at  $10 \text{ kg}/\text{cm}^2$ , 7.5 years at  $8 \text{ kg}/\text{cm}^2$ , and 16 years at  $6 \text{ kg}/\text{cm}^2$ .

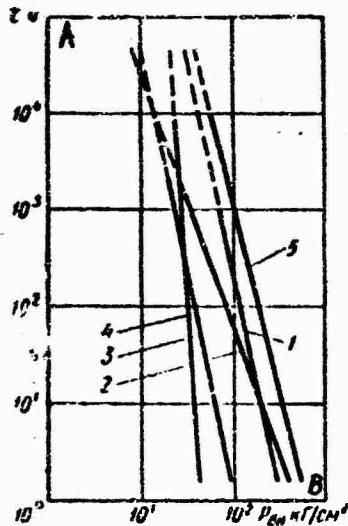


Fig. 79. Service life curves for piping made of glass-reinforced plastics (with internal gas-tight liner) when exposed to internal hydrostatic pressure:

- 1 -- based on glass yarn and PN-1 polyester resin at  $20^\circ \text{C}$  (air is external)
- 2 -- based on glass yarn and PN-1 polyester resin at  $20^\circ \text{C}$  (water is external)
- 3 -- based on glass yarn and PN-1 polyester resin at  $60^\circ \text{C}$  (air is external)
- 4 -- made by Dow-Smith Corporation (United States), at  $65^\circ \text{C}$  (air is external)
- 5 -- made of glass-reinforced plastic, at  $65^\circ \text{C}$  (air is external)

KEY: A --  $T$ , hours  
B --  $F_{in}$ ,  $\text{kg}/\text{cm}^2$

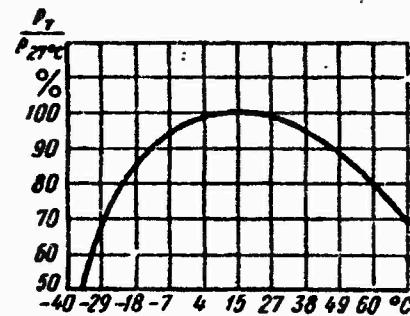


Fig. 80. Dependence of pressure ratio  $P_T/P_{270 \text{ C}}$  on temperature for piping made of glass-reinforced plastics incorporation polyester binder, fabricated by centrifugal molding (Fibercast Company, US)

The low longevity of biplastic pipes at elevated temperatures and in the presence of moisture is attributed to the low heat resistance and low moisture resistance of polyester binder based on PN-1 polyester resin used for these pipes, and also to the use in their fabrication of glass roving not treated with adhesion-waterproofing sizers.

Below are presented data on the technical level of the production of pipes made of glass-reinforced plastics attained by certain foreign companies.

The Fibercast Corporation (United States) fabricates piping from glass-reinforced plastics, by the centrifugal method, for transporting corrosive media under oil field conditions. The pipes are lined within with a protective coating based on a composition consisting of synthetic resins. The pipe length ranges from 4 to 6 m. They are supplied with smooth ends, with flanges, couplings, and also with threaded ends. Pipes are produced ranging in diameter from 60 to 220 mm.

Table 34 gives dimensions, working parameters, and the ultimate strength of pipes with external diameter of 114 mm produced by the Fibercast Corporation (United States).

Pipes made by the Fibercast Corporation (United States) fabricated with epoxy binder are recommended to be used at temperatures from -40° C to 150° C, and those fabricated using polyester binder -- from -40° C to +65° C. Fig. 80 presents the dependence of  $p_T/p_{27^\circ\text{C}}$  on temperature for pipes made of polyester binder (where  $p_T$  is the working pressure at the given temperature).

The Permali Corporation (United Kingdom) produces pipes from glass-reinforced plastics by the helical crossover winding method using glass roving at an angle of 55°, employing epoxy binder. The glass content in the plastic is 75 percent by weight.

The physicomechanical properties of the material are presented below:

Density in g/cm <sup>3</sup> . . . . .	1.9
Water absorption in mg/cm <sup>3</sup> . . . . .	3.5
Adsorption in mg/cm <sup>2</sup> for 1 hour of boiling . .	10
Maximum working temperature in ° C . . . . .	155
Ultimate strength in kg/cm <sup>2</sup> in tension:	
in the tangential direction . . . . .	4922
in the axial direction . . . . .	2460
Modulus of elasticity in kg/cm <sup>2</sup> in tension	
in the tangential direction . . . . .	$2.46 \cdot 10^5$
Modulus of elasticity in kg/cm <sup>2</sup> in torsion . .	$7 \cdot 10^4$

The dependence of internal burst hydrostatic pressure on diameter and wall thickness for given pipes is shown in Fig. 81.

TABLE 34. SPECIFICATIONS OF PIPING MADE OF GLASS-REINFORCED PLASTICS WITH EPOXY RESIN  
FOR DIFFERENT SERVICE CONDITIONS

Назначение труб /	БСС 1 и 2 кг на типы 6 и 8 кн трубы сече- нием 4 и 3 мм	Диаметр диаметр работы в мм при температу- ре в °C 27 150	Внутреннее рабочее давле- ние в кг/см <sup>2</sup> при температу- ре в °C 5 15 20		Паспортные зна- чения в кг/см <sup>2</sup> при температу- ре в °C 27 20	Паспортные зна- чения в кг/см <sup>2</sup> при температу- ре в °C 27 20	Паспортные зна- чения в кг/см <sup>2</sup> при температу- ре в °C 27 20	Паспортные зна- чения в кг/см <sup>2</sup> при температу- ре в °C 27 20
			7	8				
Для химически агрессив- ных сред /1/	3,89	6,6	5,3	24,6	11,9	2721	36,8	211
Для легких условий экс- плуатации в химических загрязненных водах и дре- нажных стоках /2/	3,65	4,6	3,1	10,5	5,3	1814	15,8	105
Для тяжелых условий эксплуатации в нефтепро- водах /3/	3,89	7,6	6,0	35,1	17,5	2948	52,7	225
Для легких и средних условий эксплуатации в нефтепроводах /4/	2,65	3,0	2,1	10,5	8,7	1814	21,1	91
Для тяжелых условий эксплуатации в общих тру- бопроводах /5/	4,46	7,6	6,4	36,6	35,1	4535	49,2	232
Для легких и средних условий эксплуатации в хвостовых фракциях /6/	3,89	5,6	5,3	26,2	24,6	2722	36,9	211

[KEY to Table 34 is given on the following page]

KEY [to Table 34 on preceding page]:

- 1 -- Function of piping
- 2 -- Weight of 1 m in kg
- 3 -- Thickness of piping wall in mm
- 4 -- Thickness of reinforced section of wall in mm
- 5 -- Internal working pressure in kg/cm<sup>2</sup> at listed temperature in °C
- 6 -- Axial tensile (working) load in kg at 27°
- 7 -- Internal pressure during testing, in kg/cm<sup>2</sup>
- 8 -- Internal burst pressure in kg/cm<sup>2</sup>
- 9 -- External burst pressure in kg/cm<sup>2</sup>
- 10 -- Rupture load in tension, in kg
- 11 -- For chemically corrosive media
- 12 -- For mild conditions of using chemically contaminated water and sewage discharge
- 13 -- For severe conditions of use in petroleum pipelines
- 14 -- For mild and moderate conditions of use in petroleum pipelines
- 15 -- For severe conditions of use in general pipelines
- 16 -- For mild and moderate conditions of use in tailing fractions

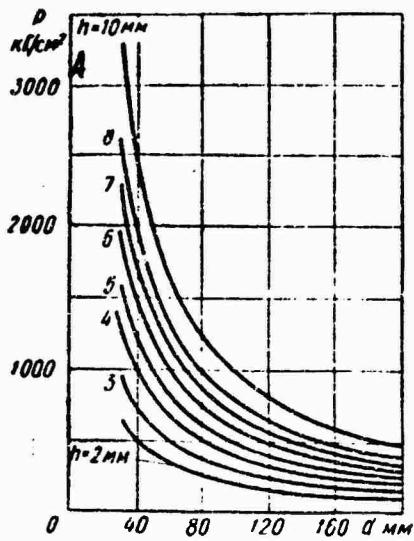


Fig. 81. Dependence of internal burst pressure  $p$  on inner diameter  $d$  of piping made of glass-reinforced plastics, for different wall thicknesses  $h$  (Permalite Corporation, United Kingdom)

KEY: A --  $\text{kg}/\text{cm}^2$

The Bristol Aeroplane Plastics Corporation (United Kingdom) produces pipes from glass-reinforced plastics using epoxy binder ranging in diameter from 100 to 400 mm.

Fig. 82 presents the recommended values of the working pressures for pipes, dependent on their diameter and wall thickness.

Dow-Smith Corporation (United States) produces pipes from glass-reinforced plastics using epoxy binder. Depending on the service conditions, the pipes are divided into three types: RTP-70 -- for mild service conditions with static loading; RTP-110 -- for moderate service conditions with cyclic loading; and RTP-190 -- for severe service conditions with cyclic loading.

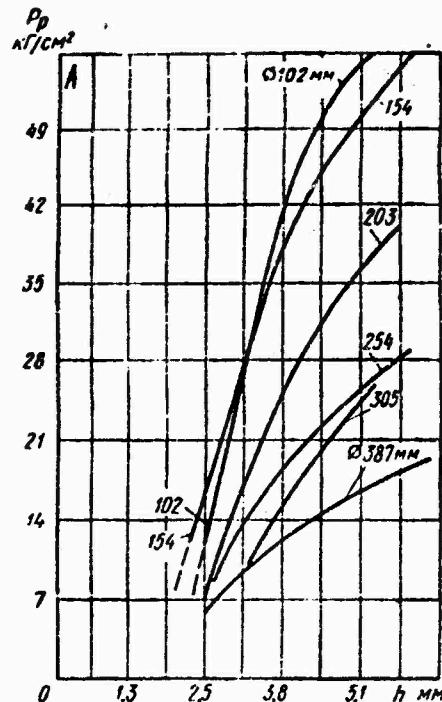


Fig. 82. Dependence of working pressure  $P_p$  for piping made of glass-reinforced plastics using epoxy binder on wall thickness  $h$  for different diameters (Bristol Aeroplane Plastics, United Kingdom)

TABLE 35. CHARACTERISTICS OF PRESSURE PIPES MADE OF REINFORCED PLASTICS USING EPOXY BINDER

1 Тип труб	2 Условный диаметр в мм	3 Наружный диаметр в мм	4 Толщина стенки в мм	5 Масса 1 м в кг	6 Предельное рабочее давление при испытании в кг/см <sup>2</sup> при температуре 65° С	7 Давление при испытании в кг/см <sup>2</sup>	8 Пределы при нарушении герметичности в кг/см <sup>2</sup>	9 Расстояние между опорами в м
RTP-70	50	60,3	1,8	0,6	21	84	175	2,4
	76	88,9	1,8	0,9	14	56	140	2,7
	102	114,9	1,8	1,19	10,5	42	84	2,9
	152	168,2	1,8	2,52	10,5	42	87	3,3
RTP-110 RTP-190	50	62,2	2,8	0,74	35	112	252	2,5
	50	59,6	4,8	1,8	84	168	385	2,5

Remarks: 1. Length of fabricated pipes is 7.6-9 m.  
 2. Piping is tested with hydrostatic pressure, with an exposure 1 min.

3. Maximum pressure upon the disruption of gas-tightness is determined at a loading rate of 70 kg/cm<sup>2</sup> per minute.

4. Distance between supports is determined on the basis of the sizing of piping (12-25 mm) under its own weight.

KEY: 1 -- Model of piping  
 2 -- Standard diameter in mm  
 3 -- Outer diameter in mm  
 4 -- Wall thickness in mm  
 5 -- Weight of 1 m in kg  
 6 -- Maximum working pressure in kg/cm<sup>2</sup> at 65° C  
 7 -- Pressure in testing in kg/cm<sup>2</sup>  
 8 -- Maximum pressure with the disruption of gas-tightness in kg/cm<sup>2</sup>  
 9 -- Distance between supports in m

Specifications of these pressure pipes are given in Table 35. The pipes are produced without internal gas-tight layer. Therefore the limiting condition for these pipes is a breakdown in gas-tightness, which is reflected in the specifications.

TABLE 36. INDICATORS OF THE MECHANICAL PROPERTIES OF  
PIPING MADE OF GLASS-REINFORCED PLASTICS AT 22° C

Показатели	2 Значение показателей для труб типа	
	RTP-70, RTP-110	RTP-190
3 Предел прочности в кг/см <sup>2</sup> при ра- стяжении: 4 в осевом направлении 5 в тангенциальном направлении	630 2800	2690 —
6 Предел прочности в кг/см <sup>2</sup> при сжа- тии	945	1900
7 Модуль упругости в кг/см <sup>2</sup> : 8 при растяжении 9 при сжатии	8·10 <sup>4</sup> —	19·10 <sup>4</sup> 8,8·10 <sup>4</sup>
10 Относительное удлинение при раз- рыве в %	2,0	2,1
11 Водопоглощение за сутки в %	—	0,118

Remark. Pipes exhibit long service life (cf. Fig. 79)

KEY: 1 -- Indicator

- 2 -- Values of indicators for piping of models listed
- 3 -- Ultimate strength in kg/cm<sup>2</sup> in tension
- 4 -- In axial direction
- 5 -- In tangential direction
- 6 -- Ultimate strength in kg/cm<sup>2</sup> in compression
- 7 -- Modulus of elasticity in kg/cm<sup>2</sup>
- 8 -- In tension
- 9 -- In compression
- 10 -- Relative elongation at rupture in %
- 11 -- Water absorption in 24 hours in %

The mechanical properties of these pipes are given in Table 36.

Based on the data of the report [91], glass-reinforced plastic pressure pipelines can serve underground. Their stiffness -- EI, where E is the modulus of elasticity and I is the moment of inertia of the cross-section, is of determining importance in this case. Piping made of glass-reinforced plastics fabricated by longitudinal-transverse winding are used for this purpose.

Piping made of glass-reinforced plastics fabricated with epoxy resin [91] has the following dimensions and mechanical properties (pipe diameter 200 mm):

Wall thickness in mm . . . . .	1.9
Length in m . . . . .	to 18
Weight of 1 m of pipe in kg . . . . .	2.2
Internal burst pressure in kg/cm <sup>2</sup> . . . . .	20
Ultimate strength in kg/cm <sup>2</sup> of piping in tension in the tangential direction . . . . .	1050
Ultimate strength in kg/cm <sup>2</sup> in compression in the tangential direction . . . . .	2940
Stiffness EI for piping with wall thickness 2.8 mm	418
Range of working temperatures in ° C . . . . .	From -40 to +120

In Finland, pipes are produced from glass-reinforced plastics serving various purposes. The company name of the glass-reinforced plastics is Corrodvr.

Corrodur-T with polyester binder is used in making pipes serving at temperatures from -40 to +70° C.

Corrodur-N based on isophthalic polyester resin is used in fabricating pipes serving in weak solutions of acids and alkalis with pH to 10 at temperatures from -40 to +120° C.

Corrodur-S with polyester binder based on bisphenol is used in making pipes serving in the chemical industry at temperatures from -40 to +140° C.

Corrodur-H based on correlated polyester resin (noncombustible glass-reinforced plastic) is used in making pipes serving at temperatures from -40 to +160° C.

Corrodur-E, an epoxy polyester glass-reinforced plastic, is used in making pipes that are stable in solutions of acid and alkali at temperatures from -40 to +70° C.

The pipes are made with a diameter range of 27 to 3000 mm, 5 m in length, and the wall thickness is as ordered.

Physicomechanical properties of these pipes are as follows:

Ultimate strength in tension in kg/cm <sup>2</sup>	1100 - 3000
Ultimate strength in compression in kg/cm <sup>2</sup>	1200 - 2400
Modulus of elasticity in kg/cm <sup>2</sup>	60·10 <sup>3</sup> - 200·10 <sup>3</sup>

Coefficient of thermal conductivity in kcal/(m·hr·deg) 0.2 - 0.3

Relative temperature coefficient of linear expansion

in  $\text{deg}^{-1}$

$15 \cdot 10^{-6}$  -  $30 \cdot 10^{-6}$

### Shaped Pipeline Parts

The diversity of shaped parts of pipelines made of reinforced plastics makes it difficult to devise and improve mechanized technology of their manufacture. Difficulties in fabricating tee-pieces, branch pipe, and unions of different types are due to the fact that they are articles of complex configuration. The main difficulty which must be encountered in molding such articles lies in extracting the cores. Stiff and elastic cores are used. Stiff cores are fabricated, for example, of plastic, easily melted alloy, and so on. The cores are removed by fracturing or melting after the shaped part has been produced. Sometimes walls of pre-molded thin articles are cut through, the core is removed, and then additional molding is continued until the required wall thickness is achieved.

Depending on the working pressures, in some domestic enterprises fittings are conventionally divided into three categories: high-strength ( $p_w \geq 100 \text{ kg/cm}^2$ ), moderate strength ( $p_w = 64 \text{ kg/cm}^2$ ), and low-strength ( $p_w \leq 24 \text{ kg/cm}^2$ ).

Depending on the fitting category, the corresponding kinds of reinforcing materials are used.

Glass cloth and glass roving cut out by template and wound on the core are used as reinforcing material for high-strength articles.

Combination glass-reinforced plastic based on glass cloth and chopped fiber is used in making moderate-strength fittings. In this dry state, initially the cut-out glass cloth is wound on a perforated core, and then chopped glass fiber containing binder is deposited, after which impregnation with binder is carried out.

Low-strength fittings are fabricated from glass-reinforced plastic based on chopped glass fiber, which is suctioned on a perforated core and is then impregnated.

Sometimes built-up molds and built-up cores are used in making fittings.

The Bristol Aeroplane Plastics Corporation (United Kingdom) has developed specifications and has set up the production of shaped articles made of reinforced plastics for pipelines with diameter of 100, 150, 200, 250, 300, and 400 mm for working pressures to  $10 \text{ kg/cm}^2$  and for temperatures to  $60^\circ \text{ C}$ .

Fittings were developed for pipelines made of glass-reinforced plastics of various functions (RTP-70 and RTP-110 types). They are prepared from a compound based on epoxy resin reinforced with glass fiber. The connecting surfaces of fittings are adapted for cementing. The conical section or the threading is used for this purpose.

#### Basic Rules in the Assembly, Testing, and Operation of Pipelines

Pipes made of glass-reinforced plastics can serve in closed quarters as well as in open air on trestles year round, in any climatic conditions. Pipes made of glass-reinforced plastics are assembled simultaneously with the installation of process equipment, metal structures, and all necessary metal pipelines passing near or parallel to the glass-reinforced plastic pipelines. Glass-reinforced plastic pipes and shaped parts received for installation are carefully inspected and the defective areas are corrected.

Pipelines made of glass-reinforced plastics are installed in the following order:

- laying out of the route and placement of support structure;
- laying out and fabrication of openings for the placement of suspension fixtures;
- installation and checking of suspension fixtures;
- installation of support fittings;
- fabrication of sections of 2-3 pipes in length with their laying-out and fitting;
- placement of sections on support fixtures and their connection;
- checking of the line and tightening of collars;
- placement of end fittings;
- hydraulic testing of the pipeline; and
- flushing of the system with tap water and painting of all external metal parts of the pipeline.

In laying out the route, the necessity for inclining the pipeline in order to prevent plugging must be taken into account, and the inclination is provided for toward the side of liquid flow. The allowed deviation in marked axes in the horizontal plane must not exceed  $\pm 3$  mm per each 10 m of route length. The minimum inclinations of pipelines made of glass-reinforced plastics per m of length in transporting water, acids ( $H_2SO_4$ , HCl, and  $HNO_3$ ) and petroleum products is 3.5 and 12 mm, respectively.

When necessary, it is allowed to lay out the pipelines made of glass-reinforced plastics with epoxy binder with some curvature of their axis, followed by securing on supports. The minimum radius of curvature for pipe diameter of 50 mm is 24 m; it is 33 m for pipe diameter of 76 mm; it is 45 m for a pipe diameter of 102 mm; and it is 63 m for pipe diameter of 152 mm.

The distance between supports in the installation of pipelines made of glass-reinforced plastics, according to the data of the Bristol Aeroplane Plastics Corporation (United Kingdom) is taken as follows:

Internal pipe diameter in mm	100	150	200
Distance between supports in m	1.2-1.8	1.8-3.0	2.4-3.6
Internal pipe diameter in mm	250	300	400
Distance between supports in m	3.0-4.5	3.5-5.4	4.5-6.0

The Fibercast Corporation (United States) recommends that the distance between supports, when pipes made of glass-reinforced plastics are being installed, be chosen as the function of their external diameter and the temperature of the medium being transported on the condition of maximum sag of 13 mm (Figs. 83 and 84).

The distance between supports of pipelines made of glass-reinforced plastics of the Corrodur type is chosen from Table 37.

In installing pipelines made of glass-reinforced plastics, the following main principles must be followed:

the support collars must fit tightly against the pipe and permit only axial displacements of the pipe;

the support must not permit vibrations of the pipelines, since otherwise loss of gas-tightness of the joints can take place;

when pipes are laid, they must not be allowed to directly contact the metal parts of supports and collars, since the glass-reinforced plastic functions poorly with abrasion;

rubber or elastic spacers must be used;

the rubber spacers between pipe and collars must have sufficient thickness (3-4 mm) and must permit a temperature expansion of the pipe in the radial direction. Excessive tightening of collars is not allowed, since with time during service the rigidity of pipe at the securing site can be disturbed;

individual mounting of shaped parts must be provided for; each branch pipe must be secured with collars at two points;

it is allowed to place pipelines made of glass-reinforced plastics on suspension fixtures without collars. Here is also desirable to increase the area of pipe contact with the suspension fixtures by using rubber spacer; and

protective gutters or liners must be placed under the pipelines over passageways, work stations, and door openings.

When installing pipelines made of glass-reinforced plastics, use is made of any pressure fittings (valves, cocks, and valve gates) employed for pipelines made of other material and corresponding to the service conditions. However, the fixtures in this case must be secured separately so that the forces produced in closing and opening during the service period are not transmitted to the pipeline.

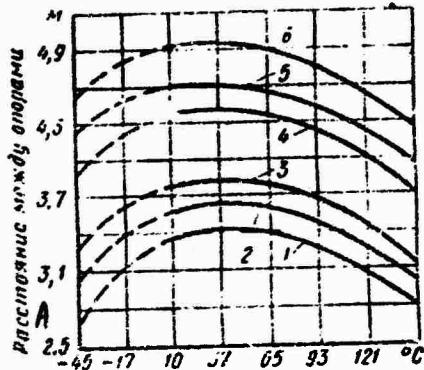


Fig. 83. Dependence of distance between supports on temperature and outer diameter for piping made of glass-reinforced plastics with epoxy resin, fabricated by centrifugal molding:

- 1 --- for  $D = 60 \text{ mm}$
- 2 --- for  $D = 73 \text{ mm}$
- 3 --- for  $D = 89 \text{ mm}$
- 4 --- for  $D = 144 \text{ mm}$
- 5 --- for  $D = 168 \text{ mm}$
- 6 --- for  $D = 219 \text{ mm}$

KEY: A --- Distance between supports

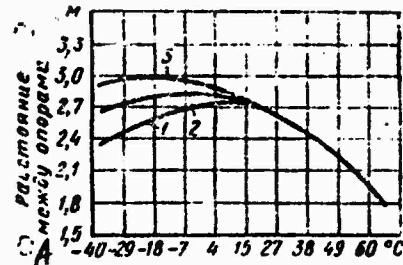


Fig. 84. Dependence of distance between supports on temperature and outer diameter D for piping made of glass-reinforced plastics with polyester binder, fabricated by centrifugal molding:

- 1 --- for  $D = 60 \text{ mm}$
- 2 --- for  $D = 89 \text{ mm}$
- 3 --- for  $D \geq 114 \text{ mm}$

KEY: A --- Distance between supports

TABLE 37. DISTANCE BETWEEN SUPPORTS FOR PIPING MADE OF CORODUR GLASS-REINFORCED PLASTICS

1 Внутренний диаметр трубы в мм	Расстояние между опорами в м при транспорти- ровке	
	2 3 жидкости	4 газа
50	2,0	3,0
100	2,5	4,0
200	3,0	5,0

- KEY:
- 1 --- Inner diameter of piping in mm
  - 2 --- Distance between supports in m during the transporting of material listed
  - 3 --- Liquid
  - 4 --- Gas

Glass-reinforced plastic pipelines can be laid in unfilled trenches. Here the immobilization is achieved with metal brackets mounted in the walls or the base of the trench. Concrete slabs overlap these trenches. In order to provide for observation of the condition of the pipelines during their service time, inspection wells are provided at a distance of 5-6 m from each other and in the location of fittings. It is not mandatory to keep these pipelines warmed.

When there is not enough support column, rigid flooring made of metal beams must be fabricated in order to secure the pipes to them.

The allowable working pressure in a pipeline made of glass-reinforced plastic depends on a number of factors. Most important of these is the quality of the pipes, cladding layer, shaped parts, and kind of connections. The strength margin for pipe material is taken to be 10-fold with allowance for long-term service at elevated temperatures. We know that the design of the connections strongly affects the bearing capacity of a pipeline. Permanent connections (unions and banding) permit higher temperatures in the pipeline compared to removable connections (flange and threaded types).

Installed pipelines made of glass-reinforced plastic are tested for hydraulic pressure that is greater than the working pressure by a factor of 1.5. The operation of the pipeline without preliminary hydraulic testing is not allowed. For safety purposes, air from the pipelines is passed through a valve into a blank flange installed at the highest point of the pipeline. A test of pipelines of considerable extent is recommended to be conducted with sections up to 500 m in length.

When establishing the operating regime of pipelines made of reinforced plastics, the starting point must be the allowable working loads, temperatures, and corrosive media. Pipes made of glass-reinforced plastics are not brittle and withstand dynamic loads. However, unrelated objects must not be suspended on pipelines, especially over sections between supports, since upon prolonged exposure to concentrated loads loss of pipe rigidity is possible, along with an exceeding of the allowable sag values. Pipes whose gas-tightness has been disturbed are replaced for the section between two unions.

Depending on the kind of reinforcing material and binder used in fabricating pipes and the loading, pipes can function in the conveying of corrosive media to which the material of the facing layer is resistant at temperatures from -200 to +30 - 110° C. Pipelines are not sensitive to thermal shocks. When critical stratification develops in pipelines, it is not allowed to warm them using open flame. Pipelines situated in unheated rooms or in the open air and transporting freezable liquids during winter, must be entirely cleared of liquid when production stops. Since the thermal conductivity of glass-reinforced plastics is very low, in many cases they can be used without thermal installation. When liquids are conveyed through glass-reinforced plastic pipelines, static electricity

accumulates on pipe walls. Static electricity must be removed in this case via a current-conductive layer of varnish or paint. The layer is applied on the surface of the pipes over their entire length with a brush in one or two lines about 5 mm in width. Rubber spacers at the connection points are wrapped with a strip of aluminum or copper foil and are emplaced within the pipe in such a way that the current-conducting coatings and the foils are in contact. The pipeline is grounded with a copper wire welded to the flange.

### Compensation of Thermal Elongations of Pipelines

When the temperature of pipelines made of glass-reinforced plastics varies, the pipelines undergo thermal elongation. The elongation of a pipeline section with length  $l$ , with a rise in temperature from  $t_{ex}$  to  $t_m$  is determined by the formula

$$\Delta = \alpha (t_m - t_{ex}) l \text{ mm}, \quad (158)$$

where  $\alpha$  is the relative temperature coefficient of linear expansion ( $\alpha = (10.0-25.0) \times 10^{-6} \text{ deg}^{-1}$  for glass-reinforced plastics);  $t_m$  is the operating temperature of the pipes in  $^{\circ}\text{C}$ ; and  $t_{ex}$  is the external air temperature in  $^{\circ}\text{C}$ .

The thermal elongation of a pipeline made of glass-reinforced plastic 1 m long is 1.0-2.5 mm per each  $100^{\circ}\text{C}$  change in its temperature.

If the ends of the pipeline are rigidly secured and it cannot change length with temperature change, thermal stress is induced in glass-reinforced plastics:

$$\sigma = E \varepsilon \text{ kg/cm}^2, \quad (159)$$

where  $E = (1.5-3) \cdot 10^5$  is the modulus of elasticity in  $\text{kg/cm}^2$  when the glass-reinforced plastic is under tension; and  $\varepsilon$  is the relative elongation in percent of the pipeline upon heating, i.e., the ratio of the increment in the pipeline length to its initial length.

The calculated thermal stress must not be the allowable tensile (compressive) stress of the glass-reinforced plastic. For a cross-sectional area of the pipe equal to  $F \text{ cm}^2$ , the heated (cooled) rigidly secured pipeline proves to be compressed (stretched) with the force:  $P = \sigma F = E \varepsilon F \text{ kg}$ .

This same force will be transmitted to the supports.

The limiting calculated temperature difference, above which it is required to use compensatory devices for glass-reinforced plastic pipelines, is determined as follows:

$$\Delta t = \frac{[\sigma]}{E\alpha} = \frac{300}{225000 \cdot 20 \cdot 10^{-6}} \approx 140^\circ C.$$

where  $[\sigma] = 300-400 \text{ kg/cm}^2$  is the allowable tensile (compressive) stress of glass-reinforced plastics.

However, by allowing for the possible loss of pipe resistance and referring to available operating experience with pipelines made of glass-reinforced plastics, this temperature difference is usually reduced to  $100^\circ C$ .

When there is a large temperature drop, it is desirable that compensators be installed [33]. Ordinary  $\Gamma$ -shaped, length, and bellows compensators are employed for these cases. The pipeline can be designed with allowance for its self-compensation based on the  $\Gamma$ -shaped scheme (Fig. 85 a), with the angle between pipe axes from  $90$  to  $160^\circ C$  and with different ratios of section length from  $n = 1$  (symmetric scheme) to  $n = 5$  or by the Z-shaped scheme with the pipe axes rotated by  $90^\circ$  and with different ratios of the length of straight sections (Fig. 85 b).

Self-compensation is calculated by determining the maximum stresses induced in pipelines due to thermal strains. For the  $\Gamma$ -shaped scheme we have

$$\sigma_{\max} \approx \frac{1.5}{\cos \beta} \left( n + 1 + \frac{n+3}{n+1} \sin \beta \right) \frac{\Delta E d}{l^2} \quad \text{kg/cm}^2 \quad (160)$$

KEY: A --  $t$  accrued operating time  
where

$$n = \frac{l_1}{l}; \quad \Delta = \alpha(t_n - t_0);$$

d is the inner pipe diameter in cm.

In the particular case when the pipe axis is rotated by  $90^\circ$  ( $\beta = 0^\circ$ ),

$$\sigma_{\max} \approx 1.5(n+1) \frac{\Delta E d}{l^2} \quad \text{kg/cm}^2 \quad (161)$$

For the Z-shaped scheme,

$$\sigma_{\max}^A = \frac{1.5(4n^3 + 3n + 1)}{n^2(3n + 2)} \cdot \frac{\Delta E d}{l^2} \quad \text{kg/cm}^2; \quad (162)$$

$$\sigma_{\max}^B = \sigma_{\max}^C = \frac{1.5(8n^2 + 3)}{n(3n + 2)} \cdot \frac{\Delta E d}{l^2} \quad \text{kg/cm}^2. \quad (163)$$

when  $n > 0.63$ ,

$$\sigma_{\max}^B = \sigma_{\max}^A.$$

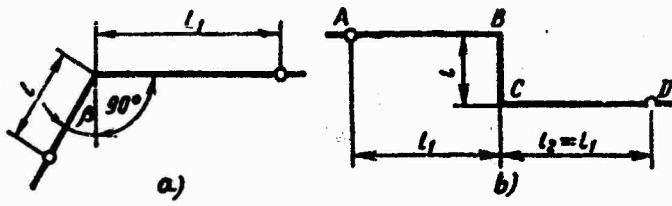


Fig. 85. Compensators:  
 a — L-shaped  
 b — Z-shaped

In L-shaped schemes with straight sections of considerable runs (greater than 15-20 m), with pipes placed on sliding supports, the actual compensating ability is smaller than the calculated value owing to the frictional resistance of the supports. The frictional forces in the supports can be neglected if in the area of the turn angles used for self-compensation the pipes are placed on ball-type supports. This makes it possible, when calculating self-compensating L- and Z-shaped schemes, to assume in all cases that the length of the straight section are equal to their geometrical length.

## CHAPTER SEVEN

### METHODS OF CONNECTING STRUCTURAL MEMBERS OF EQUIPMENT AND PIPELINES

In estimating the effectiveness of the use of equipment and pipelines in the chemical industry, the proper selection of their connections is vitally important. The choice of connections depends on the operating conditions, insulation methods, nature and magnitude of load, temperature, corrosive medium, and so on.

To ensure the reliable functioning of equipment and pipelines, the connection design must satisfy the following requirements:

- ensure that the joint is gas-tight in pressure and in vacuum;
- ensure minimum pressure head losses due to local drag factors; and
- be simple and convenient in installation, dismantling, and operation.

The kinds of connections of structural members of the equipment and pipelines made of reinforced plastics currently available can be divided into two main groups: detachable and permanent. Detachable connections are divided into, based on their design features, connections with threaded bushing screwed onto the ends of pipes being connected; flange connections for pipes and equipment; and connections with elastic ceiling members in the form of collar seals, rings, and bushings.

When connecting pipes made of reinforced plastics with threaded bushings, the latter are made of metal or pressed plastic and cemented at the pipe ends.

A special threading profile is recommended for these connection types. These connections can function at pressures to 40 kg/cm<sup>2</sup> for pipes fabricated on the basis of epoxy resin and glass yarn.

A disadvantage of these connections is the need to mold or cut the threading at the pipe ends, which considerably lowers their strength and complicate fabrication technology.

Flange connections have several design solutions: using installation flanges and slip-on flanges and crimped bushings.

Fig. 86 shows a connection with monolithic flanges. The flanges are secured with cement or with threading at the pipe ends. The flanges are made of metal or plastics (asbovoloknit [asbestos-reinforced fiber-filled molding compound] or glass-reinforced plastic).

Flanges made of glass-reinforced plastics are fabricated by pressing. The compositions of four pressing compounds are as follows: PN-1 polyester resin of 40, 40, 35, and 35 percent, respectively; chopped glass fiber -- 15, 25, 30, and 35 percent; and powdered mineral filler (alumina) -- 45, 35, 35, and 30 percent.

After fabrication, the flanges at the cemented connection are installed on the pipes, whose ends are machined helically along their outer surface.

The connection of pipes made of glass-reinforced plastics can be made in two modifications by employing crimped bushings and slip-on flanges. If the shoulder on which the slip-on flange rests is molded during the fabrication of the pipes, in this case the pipes are connected with detachable metal slip-on flanges. For the uniform distribution of the longitudinal loading on the shoulders, sometimes an elastic spacer is placed between them and the slip-on flange.

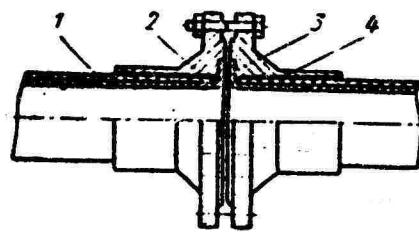
If the shoulders are made separately and cemented to the pipe, in this case a flange (Fig. 87) connection is used.

Use is made also of coupling connection similar to the connections of asbocement pipes. This type of connection consists of a coupling with two circular shoulders along its edges; rubber sealing rings fitted at the ends of the pipes being connected are installed in the coupling. Owing to the shoulders, the sealing rings do not fall out of the bushing in the functioning of the pipeline. The inner and outer diameters of the rings are correspondingly somewhat smaller than the outer diameter of the pipe and larger than the inner diameter of the bushing.

Permanent connections for pipes made of reinforced plastics can be divided into three main types: banding, bellmouth, and socket [sleeve].

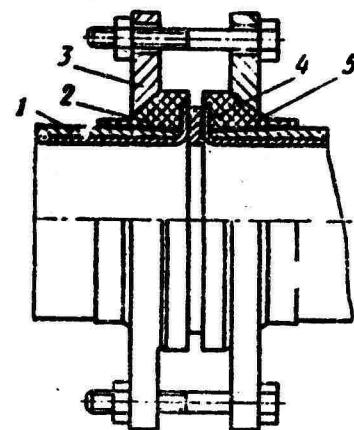
Wrap connections in glass-reinforced plastic articles provide for wrapping of the ends of pipes being joined with glass cloth or glass mat impregnated with binders. Polyester and epoxy resins are used as binders for pipes made of glass-reinforced plastics based on polyester resins. The best reinforcing material is grade T glass cloth.

Another type of permanent connections is the cemented bellmouth connection (Fig. 88). The bellmouth is made during the pipe fabrication.



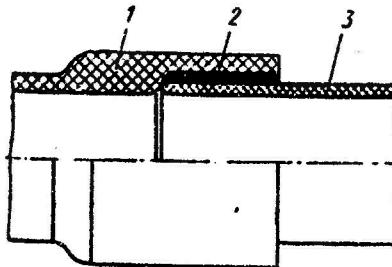
**Fig. 86.** Flange connection of pipes made of glass-reinforced plastics:

- 1 — pipe
- 2 — flange
- 3 — rubber spacer
- 4 — cement layer



**Fig. 87.** Flange connection of piping made of glass-reinforced plastics with shoulders:

- 1 — piping
- 2 — shoulder
- 3 — flange
- 4 — spacer
- 5 — cement layer



**Fig. 88.** Bellmouth connection of pipes made of glass-reinforced plastics:

- 1 — ball
- 2 — resin containing glass fiber
- 3 — pipe

Of interest is the bellmouth connection made by the Bristol Aeroplane Plastics Corporation (United Kingdom). The cement in this connection cures when heated with an electric spiral installed in the bellmouth during the fabrication of the glass-reinforced plastic pipe. This connection is mounted as follows: the end of the tube without the bellmouth is inserted into the bellmouth and the connection is wrapped

TABLE 38. ELECTRIC HEATING  
REGIME FOR CEMENTED JOINTS  
OF PIPING MADE OF GLASS-  
REINFORCED PLASTICS

Внутрен- ний диа- метр трубы в мм	Напряже- ние в в	Время наг- рева в мин	Допуска- емое сниже- ние напря- жения в в
1	2	3	4
100	65	10	45
150	70	10	50
200	90	12	65
250	85	18	65
300	110	20	80
400	115	20	85

Remark. Time of heating  
for minimum allowable voltage  
is 15 minutes.

KEY: 1 -- Inner pipe diameter  
in mm  
2 -- Voltage in volts  
3 -- Time of heating in  
minutes  
4 -- Allowable voltage  
drop in volts

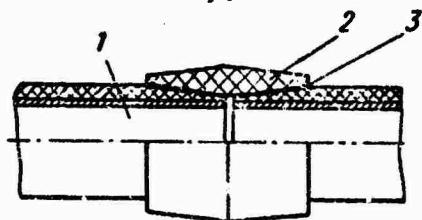


Fig. 89. Permanent sleeve joint  
of piping made of glass-reinforced  
plastics:

- 1 -- pipe
- 2 -- sleeving
- 3 -- cement layer

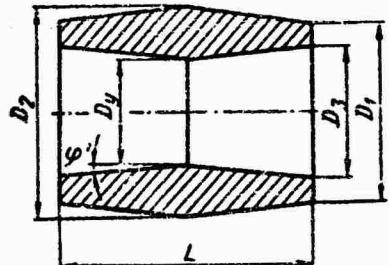


Fig. 90. Sleeving made of glass-  
reinforced plastics

TABLE 39. DIMENSIONS OF COUPLING SLEEVE IN mm

$D_s$	$D_1$	$D_2$	$D_3$	$L$	/ Massa в кг
50	70	80	60	150	0,5
80	100	110	90	150	0,7
100	130	120	110	300	1,5
125	147	155	137	300	1,9
150	173	180	163	300	2,3

Remark. Taper  $\varphi$  is 2°.

KEY: 1 -- Weight in kg

externally with a bracket or with flanges. Then resin and curing agent are forced through an opening drilled into the bellmouth. Voltage is fed to the spiral. The resin cures during heating, which ensures strong joining of the pipes being connected.

The heating regime presented in Table 38 is maintained during the cementing period.

The cemented coupling connection is the most widespread. The design of this connection provides for its construction in two types: using a straight coupling and a coupling with a bevel surface on the inner and outer sides (Fig. 89).

The couplings (Fig. 90) are made of molding compound of the same composition as the flanges. The surface of the ends of pipes made of glass-reinforced plastics can be prepared on analogy with the preparation for the flanges. A cementing connection is used to fit the couplings on the pipes. The dimensions of the couplings are given in Table 39.

An analysis of various connections of glass-reinforced plastic pipes showed that the best of these is the connection using plastic crimped bushings and slip-on metal flanges (separable) and a connection with a plastic body coupling cemented at the ends of the pipes being joined (permanent).

## CHAPTER EIGHT

### EXAMPLES OF EQUIPMENT AND PIPELINES MADE OF REINFORCED PLASTICS

#### Equipment Made of Glass-Reinforced Plastics

Employing articles made of reinforced plastics in each case must be warranted by the economic effectiveness of their fabrication and service. As an illustration of the possibility of employing reinforced plastics in chemical equipment, we present a number of typical cases of their fabrication using glass-reinforced plastics.

Equipment made of glass-reinforced plastics is used in diverse chemical lines of production. It is extensively used in storing all kinds of petroleum products (at temperatures to 130° C), dyes, bleaching and pickling solutions, solutions for nickel-plating, chromium-plating, and so on, and also in the preparation and transporting of dilute solutions of acids, alkalies, and salts (at temperatures to 60-80° C).

Equipment made of glass-reinforced plastics is also used in the manufacture, storage, and transporting of dry and liquid mineral fertilizers and poisoned chemicals. Equipment made of corrosion-resistant steels and other metals in short supply is being displaced in the manufacture of synthetic and artificial fibers by equipment made of glass-reinforced plastics. Several foreign companies use equipment made of glass-reinforced plastics to transport and store juices, wines, drinking water, and other food products [105].

Equipment made of glass-reinforced plastics serves mainly at low pressures.

#### Design Execution of Chemical Equipment Made of Glass-Reinforced Plastics

Abroad, glass-reinforced plastics are used in making vessels up to 76 m<sup>3</sup> in capacity, tanks, air lifts, and cisterns up to 50 m<sup>3</sup> in capacity, storage containers up to 200 m<sup>3</sup> in capacity [104], and columns up to 3 m in diameter and up to 15 m in height.

Equipment produced can be divided into the following classes by design execution and geometrical form: vertical and horizontal cylindrical equipment with flat and conical end-closures; rectangular, vertical, and horizontal with flat covers and bottoms; and oval with flat electrical spherical covers.

Three types of equipment are produced in terms of manufacturing execution: seamless-molded, seamless-body, and prefabricated.

Depending on the function, equipment in any execution can be fitted with hatches, connecting pipes, bubblers and repressuring pipes, partitions, mixers, and heat-exchanger elements.

Seamless-molded equipment is made by spraying chopped glass fiber and binder and also by contact molding, using glass lap and glass cloth as reinforcing materials. Here mandrels made of light metals (fusible) and also plaster (breakable) are employed. A plaster mandrel is removed from the equipment by flushing it out with hot water or by fracturing it.

Seamless-molded equipment prepared by the method of spraying glass fiber is small in size; it is intended for service under pouring conditions, since the tensile ultimate strength of these glass-reinforced plastics is in the limits 700-1200 kg/cm<sup>2</sup>.

Equipment fabricated by contact molding using glass lap is used in capacity sizes up to 4 m<sup>3</sup> for service without pressure (the strength of the glass-reinforced plastic is 1500-2000 kg/cm<sup>2</sup>). Stronger equipment units are made of glass cloth of linen, satin, and cord weave with different binders (the strength of the material is 3000-4000 kg/cm<sup>2</sup>). In contact molding, articles of different shapes are made without employing complicated industrial equipment. However, this method is labor-intensive and requires a large number of manual operations. In addition, the industrial section must be organized for the continuous fabrication of mandrels.

These equipment units are used for storing solutions of acids and salts.

Seamless-body equipment is made by wet winding. Strips made of glass lap or cord type glass cloth is used as the reinforcing material [103]. The industrial process of molding equipment walls is completely mechanized and automated in accordance with the specified regime. The article on the mandrel undergoes heat treatment in a chamber. To accelerate curing, the impregnated reinforcing material to be molded on the mandrel is additionally heated with infrared radiators. Seamless-body equipment is marked by its high strength and stiffness. It is reasonable to utilize the bearing capacity of the glass-reinforced plastic in these kinds of equipment with minimum consumption of materials: only tensile forces are transmitted to the fibers of the shell and the bottom. The ultimate tensile strength of glass-reinforced plastic, depending on the kind of binder used, varies from 8000 to 16,000 kg/cm<sup>2</sup>. In the fabrication of the equipment, glass

filaments are laid along geodesic lines [57]. The mandrels are made of fusible metals. Thus far it has not been found possible to fabricate these kinds of equipment without technological openings in the centers of bottoms, which have to be closed with removable covers.

Seamless-body equipment lined internally with rubber are used to store liquid and gaseous media at high pressures -- to 20 kg/cm<sup>2</sup>.

Fabricated equipment is the most widespread in chemical lines of production owing to the simplicity of its fabrication from a number of elements, including the use of pipes of different dimensions as semi-finished items.

Prefabricated equipment is mainly cylindrical in shape, but rectangular and spherical shapes are also found. When putting the equipment together, the shell fabricated by the winding method is cemented to the roof and bottom produced by pressing. The connecting pipe, hatches, supports, and other structural members are fabricated by pressing and are assembled with the body using cemented connections. The seams are strengthened by applying several layers of impregnated glass-reinforcing material. In several cases the strong union of the shell with the bottom is achieved by winding with glass yarn impregnated with binder. Finished pipes made of glass-reinforced plastics are often used in the assembly of equipment in making shells, hatches, connecting pieces, supports, and other structural members. Prefabricated equipment, like cisterns, can also be put together using detachable bolt connections from standard assemblies or parts. The bodies of cisterns are made of cemented connections and they are secured with steel straps or ribs made of glass-reinforced plastic. To strengthen shells made of glass-reinforced plastics, their outer surface can also be wrapped with high-strength steel wire.

#### Use of Equipment

Column equipment. Adsorbers and scrubbers made of glass-reinforced plastics are fabricated mainly by the methods of winding or contact molding of individual shell elements. Shell elements are assembled into a column using built-in flanges secured with bolt connections across a spacer. These equipment items are used in conditions when a constant temperature regime is required and when losses in heat to the ambient environment are undesirable. Column equipment functions in solutions of salts, alkalis, and inorganic acids. The allowable working temperature in equipment made of polyester glass-reinforced plastics, with long-term exposure to corrosive media is up to 40° C, and 60-70° C for periodic exposure.

For example, a scrubber 1.5 m in diameter and 3 m in height, in which the cylindrical shell members and plates are made of glass-reinforced plastic using a polyester binder, serves with exposure to nitric acid

vapor; the scrubber 1.5 m in diameter and 4.8 m in height made of polyester glass-reinforced plastics functions with exposure to vapor of hydrochloric acid and ammonia.

Baths. Baths and other vessels are made of glass-reinforced plastics in one piece and fabricated of separate sections [62]. Vessels of small and moderate size are made in one piece, and large vessels are made prefabricated. In the first case the articles are produced by the contact method of lay-up on positive molds. Using glass cloth and glass mats impregnated with polyester and other resins, valves of the following dimensions, in m, can be produced: 2.75 x 1.2 x 0.75; and 4.93 x 3.0 x 0.75. This method is extremely convenient and facilitates the fabrication of entry openings and partitions in vessels. Lateral planes of a bath are strengthened by the placement of stiffness ribs made of sheet iron or angle-bars. The edges are crimped to increase stiffness.

In the sectional method, baths are usually made of sections pressed of glass cloth and resin. The sections are fabricated with flanges and are joined with bolts on special rubber spacers. Semicircular sections with flat or spherical bottoms are used. These sections can be joined together and circular tanks of any dimension for storage of liquids can be produced.

An improved method of fabricating baths from glass-reinforced plastics is the application of combination glass-reinforced plastics using different types of resins. The internal part of the bath consists of a thin layer of the chemically more resistant glass-reinforced plastic based on epoxy or furan resin, and the exterior part of the bath consists of a glass-reinforced plastic using polyester or epoxy resin. This makes it possible to obtain strong inexpensive vessels with high chemical resistance internally. Sheets 3.2 mm thick (for example, based on furan resin and glass fiber), which are cemented with glass-reinforced textolite angle bars, are used in constructing the internal layer. Additional mechanical strength is imparted to the article by strengthening it with an external layer of glass-reinforced plastic based on polyester resin.

Baths made of glass-reinforced plastics are used in storing pickling and galvanic solutions in metal coating shops; solutions of hydrochloric, sulfuric, and acidic acids, dyes, salts, and alkalis; and oils and fuels.

The advantage of using glass-reinforced plastics in making electrolytic baths is their total inertness to solutions, as a result of which the appearance of blotches and off-colors is avoided.

For example, a sectional bath 18,200 liters in capacity, 2.5 m deep, and 4.5 m in diameter, made of glass-reinforced plastic, is used for sodium sulfate solutions ( $\text{pH} = 3$ ); the process takes place with continuous boiling at  $115^\circ \text{C}$  [62]. A bath for electrolyte, 100 liters in capacity and made of individual sheets of glass-reinforced plastic connected with "Arzamit" cement and ED-6 epoxy resin, function under production

conditions for 2 years. The maximum bath temperature was +60° C. The nickel electrolyte consists of nickel sulfate, boric acid, and sodium chloride; the solution acidity had a pH 4.5-5.2.

On comparison with baths lined with ceramic tiles, the preheating time of the bath was reduced by a factor of 2.

Baths for corrosive solutions are fabricated by the method of spraying onto negative molds. Chopped glass fiber (20-30 percent by weight) is used as the reinforcing material, and polyester resin is the binder. After curing at normal temperature, additional heat treatment is carried out. The baths are intended for service in the electroplating industry (width 0.7 m, depth 1 m, and length 3 m) and in the cellulose industry (width 1.15 m, depth 0.8 m, and length 3 m). Bath wall thickness is 5-9 mm, and the strength safety margin is 6. To increase structural rigidity, structures acting as backing parts around the edges of articles are installed in several modifications: steel pipes with inner diameter of 25 and 36 mm, No 6 steel angle-bars, 3 x 3 cm wooden beams, and shaped angle bars made of polyester glass-reinforced plastic. Stiffness ribs made of wooden beams partially justified themselves, for after the bath had been used for 3 months at elevated temperatures in a medium with pH 5.5, the solution penetrated to the beams through voids and by diffusion through the glass-reinforced plastic.

Storage tanks and containers are made of individual cylindrical shells produced by contact molding.

Good chemical stability and high strength of these structures are achieved by employing combination glass-reinforced plastics. The internal parts of the equipment are made of glass mats impregnated with furan resins and laid-up on the mold. After this layer has cured, for augmented stiffness of the structure, the shells are wound around with glass yarn impregnated with polyester resin.

Vessels to contain weak nitric acid solutions in the presence of organic solvents are recommended for additional coating internally with polyethylene or other chemically resistant thermosetting plastics.

Cold-curing resins can be used as binders in fabricating outside storage tanks and containers; these resins permit the shells to be installed directly on the site. This method is economically advantageous, since it involves using inexpensive fixtures in the form of short cylindrical cores of the corresponding dimension.

For example, a cylindrical vessel 3 m in diameter and 3 m in height, made of polyester glass-reinforced plastic, is intended for the neutralization of sulfonated oils with vigorous agitation at 71° C.

A cylindrical vessel 3.6 m in diameter and 5.1 m in height, made of polyester glass-reinforced plastic, is used to store products containing hydrochloric acid and gasoline at 50-80° C.

Alum boilers operated at 56-120° C are made of glass-reinforced plastic [23]. The evaporation cycle in these containers is 6-8 hours for alum solution acidity with pH = 2.5. Earlier, containers made of steel were lined with zinc or acid-resistant brick. In addition, alum boilers were successfully tested for use with a 38 percent sulfuric acid solution for 10 charges.

A storage tank for corrosive liquid, made of glass-reinforced plastic by the vacuum molding method using stiff glass-reinforced lap with a polyester acrylate binder, has a capacity of 1000 l. It can be used for long periods of time to store hydrochloric acid solutions under variable conditions from a vacuum of 350 mm Hg to a pressure of 0.7 kg/cm<sup>2</sup>, with a working temperature up to 100° C.

A storage tank for gasoline and diesel fuel was placed underground and made of polyester binder. The reinforcing material (glass mat, chopped fiber, and continuous fiber) was laid layer by layer. Its capacity is 22,700 l, length 6 m, and diameter 2.3 m. The proposed life is 15 years.

A storage tank of hydrochloric acid was fabricated by winding method. The fabrication was undertaken at the site. The fitting parts were made of wood. There are no structural connections. The storage tank diameter is 7 m, and its height is 5 m.

Cisterns. Cisterns made of glass-reinforced plastics have several advantages over metal cisterns. Capital outlays in fabrication are lower; there is the possibility of making multi-ply shells of various configurations; and their weight is reduced by a factor of 3-5, which is especially significant.

The strength of metal cisterns is increased by increasing wall thickness, which adds to the weight of the structure. The use of plastics makes it possible to modify during manufacturing the strength of cisterns with the suitable orientation of glass yarn in the direction in which the main stresses are applied. Cisterns are fabricated by the contact method. There have been reports on a centrifugal method of molding cistern members. Usually cisterns are fabricated by hand, using wet molds whose surfaces are coated externally with paraffin and which are polished to facilitate removing the article after curing. A binder layer is applied on the prepared mold by spraying; then a layer of glass mat or glass cloth onto which the binder is applied is laid out. The layers are rolled with a roller for consolidation and to remove air bubbles. Additional strips of glass-reinforced textolite are wound on the internal and external sides at the joint of the shell and the bottom to strengthen the connection.

The Buerger Eisenwerk Corporation (FRG) manufactures cisterns and vessels built of glass-reinforced plastic, 0.8-30 m<sup>3</sup> in capacity and up to 4 m in height, intended for transporting and storing solutions of acids, poisoned chemicals, fertilizers, and alcohols.

The TSN Bittle Plastics Corporation (United Kingdom) makes truck tanks using glass-reinforced plastics in the capacity range 1.9, 3.8, 4.5, 5.3, 10, and 13 m<sup>3</sup>. Glass mat and glass cloth based on polyester resin are used as glass fillers, and foamed polyethylene plastic is used as the thermal insulating material between the layers of the glass filler. This glass-reinforced plastic is resistant to acetic acid, formic, hydrochloric (to 35 percent concentration), and phosphoric acid, and also oils and electrolytes.

Cisterns for transporting corrosive liquids are made of glass-reinforced plastic based on epoxy resin. Their capacity is 85,000 l, weight 23.3 tons, inner diameter 2.5 m, length 17 m, and height 4.6 m. The cisterns are 9 tons lighter than steel cisterns, and 30-50 percent cheaper than cisterns made of corrosion-resistant steel.

Truck tanks made of glass-reinforced plastic using polyester binder [88] are intended for transporting alcohols and styrene. The section is elliptical (2 x 1.5 m), and the length is 17 m. The wall thickness is 9 mm. The capacity of the truck tank is 18,160 l.

Filter presses and drum filters. Plates and frames of filter presses rapidly malfunction owing to corrosion, especially in the aniline-dye industry whereas they are widely employed. Wooden plates and frames made of valuable wood break down in 2-3 months. Cast iron plates and frames are very heavy and their chemical resistance is low.

The manufacture of plates and frames of filter presses, bodies of drums, and drum filters using glass-reinforced plastics somewhat facilitates their maintenance and increases their longevity.

Plates made of filter presses using polyester glass-reinforced plastic and the pressing method at a pressure of 7 kg/cm<sup>2</sup> were tested in the production of intermediates and dyes. The product for filtration, heated to 80° C and consisting of a mixture of acids (hydrochloric, sulfuric, and nitric) with various organic impurities (toluene and aniline) was fed under a pressure of 3.25 kg/cm<sup>2</sup>. The plate thickness was 3.2 cm. In longevity, these plates exceed wooden plates by a factor of 4-6.

A rotating drum of a continuous drum filter operated in moderately corrosive media at 80° C was made of glass-reinforced plastic based on polyester binder. The weight of the filter was considerably reduced; the energy consumption was lowered; and the wear of bearings was decreased compared with a filter using a metal drum.

Lining of baths, cisterns, and other vessels. Glass-reinforced plastics are also used as lining material. Several layers of glass cloth impregnated with binder are successfully laid on the surface to be protected. For example, for the internal coating of a carbon steel cistern with one layer of glass cloth impregnated with polyester binder, the entire surface must be washed and cleaned with a metal brush ahead of time. After

lining, the cistern can function successfully to store water at 70-80° C for a year.

This is a relatively simple method of restoring old vessels made of carbon steel used with weakly corrosive media.

Glass-reinforced plastics are used as lining materials also to protect the bottoms of tanks in which oil is stored. To avoid corrosion under the coating, the bottom and walls of a tank must be cleaned ahead of time with sand blasting to a height of several centimeters from the bottom. Then a coating consisting of hot coal-tar resin is applied on the clean surface, after which the glass mat is laid out, and then also a layer of molten resin. All layers melt together and form a strong protective shell. Reinforcing with glass fiber imparts strength and some elasticity to the coating.

A rectangular bath 3 x 4 m in size, made of carbon steel, was lined with polyester glass-reinforced plastic. It is used for saponification at 75° C. After a 5-year check of its operation, its internal surface was found to be in a good condition.

A steam scrubber 0.9 m in diameter and 4.5 m in height, coated with polyester glass-reinforced plastic, showed no damage after exposure to hydrogen fluoride vapor for 4 years of service.

The flat plating of a reactor for chlorinating magnesia, 4.2 m in diameter, was in a good condition after 3 years of service.

Storage tanks and gas ducts lined with polyester glass-reinforced plastic serve at 93° C. After 4 years of duty, no signs of wear were noted.

A smokestack 0.68-2.25 m in diameter and 24 m high, lined with polyester glass-reinforced plastic, was used to remove the gaseous products of radioactive decay. A check after 1.5 years of service showed that there were no signs of wear.

#### Gas Ducts, Ventilators, and Smokestacks

Ventilation systems at chemical enterprises are often exposed to corrosive vapors and gases. For example, in the production of phthalic anhydride the entire forced-draft system is made of corrosion-resistant steel 1Kh18N9T, because the suction of phthalic anhydride vapor is accompanied by formation in the gas ducts of weak phthalic acid that attacks the entire system. Building gas ducts and ventilation systems of glass-reinforced plastics is highly promising, which is due to the technological soundness of fabricating bodies of revolution from glass-reinforced plastic (winding on a mandrel) and the ease of their installation.

Ventilation gas ducts are connected in two ways: flange and cement methods.

A hood 6.6 m in diameter and a fan 1 m in diameter, made of polyester glass-reinforced plastic, operate with exposure to the vapor of 6 percent sulfuric acid at 100° C. No damage was found after 3 years of service.

A ventilation gas duct 0.57 m in diameter, made of polyester plastic, was installed in place of a gas duct made of monel metal that had served for only 2 years. The new gas duct successfully functioned for 5 years with exposure to the vapor of 30 percent sulfuric acid.

A ventilation gas duct 0.3-0.47 m in diameter, made of polyester glass-reinforced plastic and intended to remove vapor from metal-plating baths, was in good condition after 5 years of duty.

A smokestack 0.71 m in diameter made of polyester glass-reinforced plastics functions in an environment of 4-15 percent nitric acid vapor at 46° C. Inspection after 5 years showed that it was in a good condition.

Pipes made of glass-reinforced plastics have been installed in several plants in the forced-draft systems to remove the vapor of sulfuric acid and moist sulfur dioxide into a mixing chamber.

All materials previously used for these purposes did not give good results. Steel became unsuitable for building the chamber and the smokestack owing to intense corrosion; the use of lead coatings posed difficulties due to an increase in the weight and creep of lead.

Aluminum piping malfunctioned after 3 months; leaks appeared in the hottest part of the piping. A smokestack was hand-molded for these purposes using glass cloth with furan resin. This temporary structure functioned well for 3 years, during which there was no cracking of the resin.

The gas temperature in the middle of a pipe 1914.4 mm in diameter was 154° C, and 40° C at a distance 95.4 mm from the pipe walls.

The smokestack was made of glass-reinforced plastic based on polyester resin to achieve high strength. A year of continuous service of the pipe afforded satisfactory results. A comparison of the cost of several materials suitable for the fabrication of the smokestack showed that polyester glass-reinforced plastics are the most economical.

A forced-draft system made of polyester glass-reinforced plastic was built to remove the vapor of ammonium chloride and hydrochloric acid in a pickling shop. The forced-draft system consisting of steel breaks down under these conditions every 3 years owing to its being attacked by corrosive vapor. The draft hoods, pipelines, and ventilation piping made of glass-reinforced plastic based on polyester resin revealed no signs of

failure under these conditions after 6 years of duty. The cost of the ventilation system consisting of glass-reinforced plastics based on polyester resin is 50 percent greater than the same system made of steel, but the latter requires a replacement of 3 years and during this time the cost of repair and upkeep is equal to the initial cost of the entire system.

A smokestack made of glass-reinforced plastic using polyester binder by the method of helical crossover winding using glass yarn successfully functioned for several years. The internal surface of the pipe had a protective layer of asbestos and phenolic resin. The height of the pipe was 9 m, diameter 2 m, and weight 4.5 tons. Internally it was exposed to sulfuric acid vapor. A steel pipe malfunctioned due to corrosion.

Purifying equipment for evacuating a stream of corrosive gases from condensers and driers have been installed at a fertilizer plant [89].

A smokestack (89 m in height and 1.5 m in diameter), a scrubbing tower (12 m in height and 2 m in diameter), gas ducts, and recirculation lines were also made of polyester glass-reinforced plastic. The smokestack was installed in metal structures. The pipe was coated internally and externally with chemically resistant resin against exposure to hydrofluoric acid, formed by the reaction of corrosive vapor with moisture.

Ventilation pipes of rectangular cross-section 1.5 x 0.9 mm were produced in segments 1.2 m long, made of polyester glass-reinforced plastic, and clad internally with 2 mm thick polypropylene, with tips in the form of shoulders and flanges. The suction hoods were made in one piece, up to 4.8 m in length.

Plant smokestacks 39.5 m in height and 1.65 m in diameter were made of polyester glass-reinforced plastic. Their specific strength is 5 times greater than steel smokestacks. The sections were fabricated by the method of winding using polyester binder. The smokestacks are intended to carry off furnace gases at 343° C [86].

Ventilation pipes with an inner diameter of 133 mm successfully served [38] to carry off acid vapor from production shops. The total length of the gas ducts was 250 m. They were made by winding on a mandrel glass yarn impregnated with polyester resin.

#### Experience in Using Glass-Reinforced Plastic Piping

The industrial manufacture of pipes made of glass-reinforced plastics is increasing year by year. Favorable experience in their use by the chemical industry is on record.

The main problem in the chemical industry is corrosion. For this reason the most serious difficulties in the functioning of pipelines arise

in basic chemical processes, synthetic fibers, chlorination, pickling, bleaching, and so on.

In 1963 680 tons of glass-reinforced plastics were used in making pipes in the United States, which is about half of the total volume of glass-reinforced plastics fabricated by the winding method.

H. Boggs and E. Edmisten [84, 92] studied the stressed state of glass-reinforced plastic pipes tested in 380 typical corrosive media. Analysis showed that at 26° C the pipes were resistant in 320 media, in 284 media at 82° C, and in 216 media at 126° C.

Increased chemical resistance in acids, alkalis, salt solutions, oils, solvents, and other corrosive media makes it possible to widely employ pipes made of glass-reinforced plastics in the chemical industry.

At the present time several corporations and companies have already accumulated some experience in the successful use of pipes made of glass-reinforced plastics in the chemical industry. The American Cyanamide Corporation (United States) makes extensive use of glass-reinforced plastic pipes in its systems for transporting corrosive media. This has meant solving many problems related to intense corrosion. The time and labor in repairing many pipeline systems have been sharply reduced.

The high cost of pipes made of glass-reinforced plastics compared to steel pipes is compensated by a reduction in the outlays associated with the upkeep and extension of their service life. One of the biggest pipeline systems fabricated thus far by a corporation was installed at a plant producing pharmaceutical preparations. Most pipelines of the system had a diameter of 203 mm, and the main collectors had a diameter of 558 mm.

In general, vapor of hydrochloric acid, butanol, and triethylamine circulate through the pipelines. These intensely active mixtures cause corrosion of galvanized iron with a phenolic coating after 6 months of continuous service.

The cost of the system of glass-reinforced plastic pipelines based on polyester resin was 2 times higher than the cost of the pipeline system made of sheet steel with phenolic coating. However, here we must bear in mind that the polyester glass-reinforced plastic system has a presumed service life of 5 years.

The considerably savings afforded by pipes made of glass-reinforced plastics when introduced into lines conveying corrosive products is graphically illustrated experience of the Sunray and Oil Company (United States) [102]. A company replaced some of its carbon steel pipes with pipes made of glass-reinforced plastics in long-run lines of its isomerization facility transporting hydrochloric acid and its vapor, and also pipelines in its alkylatic facility transporting weak sulfuric acid, as well as in its bauxite-filtering unit. Steel pipes in these conditions serve

for only 3 months, while glass-reinforced plastic pipes function for upwards of 4 years without signs of failure.

The U. S. Borax Corporation (United States) has replaced about 2400 m of pipe made of copper-aluminum alloy transporting slurries in the production of potash with glass-reinforced pipes (ranging in diameter from 76 to 254 mm). The cost of the pipelines made of glass-reinforced plastics is one third below the cost of the metallic pipeline replaced. Here the service life of the metallic pipeline is 6-9 months, but the system of glass-reinforced plastic pipelines functions from 2 to 3.5 years without visible damage. Reinforced piping is 60 percent lighter than metal piping, which considerably reduces labor outlays in installation.

Pipes made of glass-reinforced plastics found successful use at petroleum refineries [81]. The pipes are made of high-strength glass and acrylic fiber and epoxy resin using the winding method. The direction in which the glass-reinforcing material is wound is such that the piping is equally strong in the longitudinal and tangential directions. Pipes contain 30 percent resin and are made for working pressures of 11, 21, 28, and 42 kg/cm<sup>2</sup> (at 23° C): with inner diameter 152 mm for a pressure of 28 kg/cm<sup>2</sup>; with inner diameter of 203 and 305 mm for a pressure of 21 kg/cm<sup>2</sup>; and with an inner diameter of 387 mm for a pressure of 11 kg/cm<sup>2</sup>. The pipes are delivered in length of 6 m with a standard set of tees, elbows, and flanges. At the enterprise the fabricated pipes are tested with a hydraulic pressure equal to double the working pressure. A strength safety margin is 4 for these pipes. The pipes are connected with flanges and bands. Special portable equipment and accessories for wrapped and effective connection of pipes in the field have been dealt. Using this equipment, three workers can lay 60 m of 152-mm diameter pipe per hour.

An experimental section of 150 mm piping was installed in the sulfuric acid facility of a petroleum refinery. A mixture of petroleum, sulfuric acid, and coke particles was transported through the pipes. It was also proposed to use these pipes in the facility making styrene monomer. The ends of the pipes can be smooth, threaded, or can be shaped with a bell-mouth configuration. Flange, threading, and cemented connections are used in joining the pipes.

The Bristol Aeroplane Plastics Corporation (United Kingdom) has successfully used its pipes for 2 years at an ammonium sulfate plant [81]. Two test sections of 152-mm diameter pipes were installed in the plant. One line transported an unsaturated ammonium sulfate solution with a concentration of 53 g per 100 ml and a free ammonium content of 10 g per 100 ml in the temperature range 70-100° C at pressures to 1 kg/cm<sup>2</sup>.

An unsaturated ammonium sulfate solution was transported in another line. Traces of arsenic, aluminum, lissapol [a surfactant], sodium chloride, and also sulfuric acid at a concentration of 0.35 g per 100 ml were present in the solution. The working temperature of the solution was 80° C; its pressure was 1 kg/cm<sup>2</sup>. These experimental sections function satisfactorily for 2 years.

The company also installed glass-reinforced plastic pipes for transporting gas -- sulfur dioxide containing traces of hydrocarbons and fine coke particles. This line operated at temperatures from 20 to 25° C. Lead pipes that were formerly used for these lines required frequent replacement.

An experimental section of glass-reinforced plastic piping using epoxy binder with flange connections was installed to transport sodium chloride brine containing gaseous chlorine. The temperature of the medium was 80° C and its pressure was 0.36 kg/cm<sup>2</sup>. Tests on experimental pipe section proceeded satisfactorily. Pipelines made of corrosion-resistant steel previously installed at the plant rapidly malfunction due to corrosion.

The Amerkote Corporation (United States) manufactures pipes made of glass-reinforced plastics with inner layer of a mixture of epoxy or polyester resin with asbestos, exhibiting high chemical resistance.

The Stauffer Chemical Corporation employed these pipes for facilities transporting solutions of caustic soda [86]. The working conditions of the pipeline were as follows: pressure 7 kg/cm<sup>2</sup>; temperature 149° C. The pipes function successfully for 4 years.

Most of the pipes were installed at plants making electrolytic chlorine for filtration systems and in alkali-transporting lines. The pipes employing epoxy binders proved themselves in transporting strong oxidants; the tests were conducted with lines transporting wet chlorine.

The Hooker Chemical Corporation installed a system of pipes made of glass-reinforced plastics 3218 m in length to transport chlorine and caustic soda at an enterprise producing chlorine. The pipeline system functions at a temperature 80° C, a pressure of 6.5 kg/cm<sup>2</sup>, and a transporting speed of 2-3 m/sec for the medium conveyed. The metallic unprotected and rubberized pipes employed in this facility had a service life of not more than 4 years owing to electrolytic corrosion. The use of glass-reinforced plastic pipes made it possible to considerably increase the wear resistance of the pipes compared with the kind formerly used.

At a dye plant of one of the American corporations, pipes made of glass-reinforced plastics using polyester binder were employed to transport chlorinated water, and hydrobromic and hydrochloric acids in combination with organic solvents. The pipeline system has now functioned for 6 years, while pipelines made of nickel and rubberized steel functioned for a maximum of 12-14 months. The positive feature of the system is its resistance to flame.

The Hooker American Corporation successfully used pipes made of glass-reinforced plastics to convey heated saturated solutions of potassium and sodium used in the electrolysis of hot benzene.

A system of pipelines made of glass-reinforced plastics for hot brines and the vapors of hydrochloric acid and chlorine proved to be more economically advantageous than a system of steel pipelines.

The Swedish Hochanas Corporation uses glass-reinforced plastic pipes as sewage pipes for transporting corrosive liquids and also to remove mine waters, and so on. The use of these pipes proved effective and economically advantageous.

The Hochanas Corporation manufactures pipe in length of 5 and 10 m with inner diameter of 50, 80, 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 800, 1000, and 1200 mm, and also elbows with 45 and 90° angles, tees, and sockets corresponding to all these sizes.

When interesting feature of the use of pipes by the Hochanas Corporation is a pipeline laid in a new cellulose plant. This pipeline, 1.6 km in length, was intended to divert acidic wastewaters. The pipes have a diameter of 1000 mm and wall thickness of 5 mm.

The Hooker Chemical Corporation (United States) used a system of pipelines made of glass-reinforced plastics with polyester binder successfully at its chlorine plant. Neutral and alkaline saturated solutions of sodium chloride and potassium chloride at 78° C were successfully transported through a pipeline upwards of 3200 m in length and from 50 to 350 mm in diameter to electrolyzers, as well as conveying spent solutions containing free chlorine. The flow rate of the medium was 3 m/sec, and the pressure was 5-6 kg/cm<sup>2</sup>. There has been an experience in employing pipes made of glass-reinforced plastic based on phenolic binders. They are marked by high heat resistance (to 116° C) at pressures to 7 kg/cm<sup>2</sup>, and also by chemical resistance in concentrated mineral acids, toluene, and trichloroethylene at 70° C. Pipes using epoxy binder are used with alkaline media; these pipes retain about 70 percent of their strength after a year's use in a 30 percent sodium hydroxide solution at 70° C; in addition, they are resistant to salts and mineral acids at elevated temperatures, and to certain oxidizing media.

It has been reported [95] that 7 years of experience has been accumulated in the installation and operation of pipelines made of glass-reinforced plastics with epoxy (about 6.7 km) and polyester (about 3.6 km) binders. The pipe diameter incorporating epoxy binder varied from 50 to 812 mm, and pipe diameter incorporating polyester binder -- from 50 to 200 mm. The pipelines were operated to supply solutions of sulfuric acid at 25 percent concentration and the following salt solutions: zinc sulfate, sodium sulfate, weak solutions of sodium sulfide, and the condensate of spinning and bleaching solutions at temperatures to 102° C and pressures to 7 kg/cm<sup>2</sup>. The pipes are washed with 30 percent hydrochloric solution and 10 percent caustic soda solution at 65° C. Pipes made of glass-reinforced plastics were used in circulation and cascade systems of spinning baths, and in lines feeding condensate and soft water where ion contamination is highly undesirable in the bleaching systems.

The pipes used for the above purposes were laminated in structure: the inner reinforced layer was 0.25-0.5 mm thick with a high resin content, a chemically resistant layer not less than 2.5 mm thick with a glass content of 25-30 percent by weight, structural layers whose overall thickness was determined by the specified pipe strength, and an outer strengthening layer was increased with content. The strength and chemical resistance of these pipes were determined by the composition of the components and the manufacturing method. The best binder for oxidizing media was a resin consisting of bisphenol A and fumaric acid. Of considerable interest are the chlorinated polyester resins — products of the condensation of glycols and phthalic acid with high chlorine content. Later are successfully used in fabricating pipes used to divert gases containing acid vapors. These pipes exhibit high corrosion resistance and flame resistance (especially when 5 percent antimony trioxide is added). The best combination of chemical resistance and strength of pipes was observed for a glass fiber content of 25-40 percent by weight. A higher glass fabric content (up to 75 percent) makes it possible to obtain high-strength pipe for short-term loading, however upon contact with corrosive media the longevity in some cases is 2 months. It has been found that a serious drawback of glass-reinforced plastic pipes is the fact that when solutions are fed into them at temperatures above 82° C high thermal stresses are induced in the pipes: pipes up to 100 mm in diameter sometimes fail even without corrosive exposure for a glass fiber to resin ratio of 25:75. Increasing the diameter to 150 mm, and also the glass fiber to resin ratio to 40:60 and higher makes it possible to avoid the thermal failure of the pipes. An advantage of pipes made of glass-reinforced plastics of this design is the fact that they do not require thermal insulation at temperatures from -18 to 53° C, and also the fact that almost no condensate forms on them.

Approximately 300 m of pipe 450 and 380 mm in diameter incorporating epoxy binder was used in the drainage system in Battersea (United Kingdom), where glass-reinforced plastic pipes were replaced with ceramic piping. The discharges contain sulfuric acid and some ash, which imparts abrasive properties to the medium. The connecting parts made of Bakelite epoxy resin reinforced with glass fiber and terylene, and thus the resistance to abrasion was intensified. Studies on the fabrication and installation of pipes were conducted by the Mendip Chemical Engineering Corporation (United Kingdom). The pipes were installed in sections 3 m in length, each weighing about 40 kg. Some pipes were elliptical in cross-section, which facilitated laying them in narrow sections. Some sections were connected with sleeves using a cementing composition of glass fiber and epoxy resin. When the pipes were laid at temperatures below the curing temperature of the cementing composition, the butt connections underwent heat treatment using cover type electric heaters with hot air passed through the pipes. Pipeline operating experience showed that the pipelines function successfully in severe conditions and well withstand vibration and shock loads.

## CHAPTER NINE

### TECHNICAL-ECONOMIC EFFECTIVENESS OF THE APPLICATION OF GLASS-REINFORCED PLASTICS IN CHEMICAL MACHINE BUILDING

The use of glass-reinforced plastics in chemical machine building makes it possible to augment the longevity of equipment serving in corrosive media, reduces the weight of machines and articles, improves the technical-economic indicators of structures, sharply reduces the labor load and cost of manufacturing machines, and thus gains great economic benefit. It appears possible to attain large savings in nonferrous and ferrous metals in short supply and semifinished products made of these metals.

The use of glass-reinforced plastics sharply reduces outlays in setting up capacities to produce materials for the needs of chemical machine building.

Among the advantages of glass-reinforced plastics compared with other materials are low density, high specific mechanical strength, good chemical resistance, high dielectric indicators, good external appearance, noise absorbing and sound absorbing properties, vibration resistance, and optical properties; lower work load in fabricating articles (they are more technologically adaptable); low cost of articles in series mass production; and short duration of the production cycle in fabricating articles. As heat insulators, they reduce heat losses during industrial operations.

A particular advantage of glass-reinforced plastics over other materials is that their properties can be predetermined in advance, by modifying -- with wide limits -- the technological parameters of the fabricating process, by using various reinforcing materials, modified binders, by using vacuum impregnation, radiation curing, and so on.

To discover the expediency and technical-economic effectiveness of using pipes and equipment made of reinforced plastics for the need of the chemical industry, an economic investigation will be conducted in the following scale:

a rough calculation will be made of the cost and price of 1 meter of pipe length or other equipment as a function of the kind of reinforcing materials and binders used;

a comparative analysis will be made of the costs of pipes and equipment made of reinforced plastics and corresponding articles made of traditional materials (steel and nonferrous metals) and certain kinds of plastics (polyethylene, polyvinylchloride, faolite, and so on); and

a comparative analysis will be made of the service life of articles made of reinforced plastics with corresponding articles made of traditional materials.

For example, we have [1, 2] an approximate calculation of the cost and price of pipes made of glass-reinforced plastics with allowance for their adaptation for production. The calculation assumed the following:

the costs for the starting material and supplies was calculated in prevailing prices;

losses in starting material and rejects amounted to 10 percent of the total output of articles;

the cost of processing was determined roughly with reference to experience at existing enterprises;

in calculating prices, a 10 percent accumulation over costs was allowed;

the costs of pipes made of glass-reinforced plastics protected internally with thermosetting plastics was conventionally taken as 20 percent above the price on a comparison with unprotected pipes; and

the ratio of the reinforcing material and binder, by weight, was assumed to be 1:1 in the glass-reinforced plastic.

The calculation showed that the costs of pipes made of glass-reinforced plastic depend heavily on the starting materials used. The most inexpensive reinforcing material for glass-reinforced plastic piping at the present time is glass yarn [rovings], and the most inexpensive binders are polyester resins. The costs of currently produced glass-reinforced plastics based on glass yarn and polyester resin are within the limits 2-2 rubles 50 kopecks per kg. Table 40 gives the costs of 1 m of piping made of various materials [1]. The variety of pipes in the table was selected for pressures to 8 kg/cm<sup>2</sup> predominating in chemical facilities. As we can see from Table 40, the cost of 1 m of glass-reinforced plastic is greater than the cost of pipes made of carbon steel by a factor of 1.5-2. Thus, if the service characteristics -- service life, conditions of installation, transportation, upkeep, and so on -- are satisfactory, replacing carbon steel pipes with glass-reinforced plastic pipes is economically disadvantageous. However, in the chemical industry the service life of carbon steel pipes for several corrosive media is very limited (from several months to a year). Using glass-reinforced plastic pipes would mean under these conditions a sharp increase in the service life of the pipelines and a reduction in the costs for their repair, installation, and upkeep. Therefore for several media, with reference to the service conditions, it is economically advantageous to replace

TABLE 40

Внутренний диаметр трубы в мм A	B Цена 1 м трубы в руб. из материалов					
	Стекловолокнистых полимеров C	Сталь углеродистая D	Сталь нержавеющая марки E 1Х18Н9Т	Полиэтилен F	Фоллит G	
50	1-14	0-30	—	0-52	6-66	
80	2-16	1-46	11-59	1-87	8-72	
100	3-25	1-86	16-12	2-50	10-84	
125	5-00	2-12	18-35	3-90	—	
150	7-03	2-74	27-38	5-06	19-12	
200	10-85	4-46	50-82	9-60	22-14	
250	15-18	6-05	111-72	—	—	
300	20-16	7-60	—	—	—	

\* The piping is hot-rolled, seamless.

- KEY: A — Inner pipe diameter in mm  
 B — Cost of 1 m of pipe in rubles made of the listed material  
 C — Polyester glass-reinforced plastics  
 D — Carbon steel\*  
 E — Grade 1 Kh18N9T stainless steel\*  
 F — Polyethylene  
 G — Faolite

carbon and stainless steel pipes with glass-reinforced plastic pipes. Pipes made of glass-reinforced plastics are three-to-four times cheaper than seamless steel and faolite pipes. The cost of glass-reinforced plastic pipes is 20-30 percent above the cost of polyethylene pipe calculated for equal service conditions. However, polyethylene pipes are of limited application at elevated temperatures or when a temperature gradient is present. Therefore, in many cases the use of glass-reinforced plastic pipe instead of polyethylene pipe is technically and economically expedient.

Comparative indicators of the costs of pipes and pipelines made of glass-reinforced plastics and traditional materials in the United States are presented in Tables 41 and 42 [84].

TABLE 41. COST AND SERVICE LIFE OF PIPING MADE OF DIFFERENT MATERIALS WITH STANDARD DIAMETER OF 89 mm

<sup>1</sup> Трубы	<sup>2</sup> Относительная стоимость с учетом срока службы труб в долларах	<sup>3</sup> Относительный срок службы по сравнению со стеклопластиковыми трубами на эпоксидном связующем в %	<sup>4</sup> Причины выхода из строя
<sup>5</sup> Стеклопластиковые на эпоксидном связующем, рассчитанные на давление до 14 кг/см <sup>2</sup>	6,90	100	—
<sup>6</sup> Алюминиевые	10,45	26	<sup>6</sup> Коррозия
<sup>7</sup> Медные	14,70	74	<sup>8</sup> Коррозия
<sup>9</sup> Резиновые (шланги)	10,50	21	<sup>9a</sup> Разрушение от высокого давления
<sup>10</sup> Из углеродистой стали: <sup>11</sup> электросварные <sup>12</sup> цельнотянутые <sup>13</sup> с гальваническим покрытием <sup>14</sup> с эпоксидным покрытием	27,20 19,60 31,85 10,10	9,1 15,3 11,1 32,0	<sup>8</sup> Коррозия Коррозия Коррозия Коррозия
<sup>15</sup> Из нержавеющей стали: <sup>16</sup> марки 304-40 <sup>17</sup> марки 316-40	81,90 107,80	31,3 34,2	<sup>8</sup> Коррозия Коррозия
<sup>18</sup> Из поливинилхлорида: <sup>19</sup> марки 40 <sup>20</sup> марки 80	36,80 40,20	15,2 17,2	<sup>20a</sup> Разрушение от высокого давления и температуры
<sup>21</sup> Из асбосцемента: <sup>22</sup> марки С-100 <sup>23</sup> марки С-150	11,30 14,78	23,7 19,5	<sup>8</sup> Коррозия Коррозия

[KEY to TABLE 41 is given on the following page.]

KEY [to TABLE 41 on preceding page]:

1. Piping
2. Relative cost with allowance for service life of piping in dollars
3. Relative service life compared with glass-reinforced plastic piping using epoxy resin in %
4. Reasons for malfunctioning
5. Glass-reinforced plastics calculated for pressures to 14 kg/cm<sup>2</sup>
6. Aluminum
7. Copper
8. Corrosion
9. Rubber (hoses)
- 9a. Failure due to high pressure
10. Made of carbon steel
11. Electric welded
12. Seamless drawn
13. With galvanic coating
14. With epoxy coating
15. Made of seamless steel
16. Of grade 304-40
17. Of grade 316-40
18. Made of polyvinyl chloride
19. Of grade 40
20. Of grade 80
- 20a. Failure due to high pressure and temperature
21. Made of asbestos cement
22. Of grade S-100
23. Of grade S-150

As noted in the preceding chapter, glass-reinforced plastic pipes are used extensively in making ventilation systems and gas ducts. As a rule, pipes of industrial manufacture with wall thickness more than 5 mm are used for these purposes. Here an appreciable economic benefit is attained. However, in many cases it is economically disadvantageous to use these kinds of pipes for ventilation systems, since in most cases ventilation systems are without pressure heads (excess pressure of the order of 400 mm H<sub>2</sub>O).

The development and investigation of flexible roll type glass-reinforced plastics conducted in the All-Union Scientific Research Institute of Glass-Reinforced Plastics and Glass Fiber (VNIISPV) and the Moscow Institute of Chemical Equipment Building, with participation of the authors, (based -- KhZhKN glass lap made of continuous filaments of alumina borosilicate glass, and the binder is dry powdered aniline-phenol-formaldehyde resin No 214) showed that they can be successfully used for this purpose for a wall thickness 0.5-1.5 mm. Flexible roll type glass-reinforced plastics are prepared by pressing on a strip press with the binder cured to 89-93 percent. Parts (of ventilation systems) of circular

TABLE 42

1 Трубы	Стойность трубопроводов в долларах для труб с ус- ловными диаметром в мм (в расчете на 100 м трубопро- вода)				
	51	76	102	125	200
3 Стеклопластиковые химически стойкие	1022	1336	2006	2945	3967
4 Стеклопластиковые во- зможной прочности	1220	1660	2408	3667	5003
5 Из нержавеющей стали марки 316-40	2004	2936	3759	5836	8396
6 Из углеродистой стали гуммированные	1877	2048	2782	3669	4949

Remark. The cost of piping, connecting elements, and fittings, installation, insulation, and cathodic protection is included.

KEY: 1 — Piping

2 — Cost of pipelines in dollars for piping with listed standard diameter in mm (calculated per 100 m of pipeline)

3 — Glass-reinforced plastics, chemically resistant

4 — Glass-reinforced plastics with increased strength

5 — Made of grade 316-40 seamless steel

6 — Made of carbon steel, rubberized

cross-section with any diameters can be fabricated from flexible roll type glass-reinforced plastics, using various cements or chemical welding to connect individual blanks; the technology was developed in the Moscow Aviation Technology Institute under the supervision of Professor Ye. B. Trostyanskaya.

Airlines made of flexible roll type glass-reinforced plastics are three-four times later than steel and vinyl plastic pipes (for a wall thickness 0.8-1.5 mm), and their cost -- even under conditions of prototype production -- do not exceed the costs of airlines made of material ordinarily employed. Here, as was shown by experience in the two years' service of ventilation systems at a chemical combine, the process of their fabrication and installation is simplified and facilitated, operating outlays are lowered, and their service life is extended.

However, when selecting initial materials for the production of pipes and chemical equipment made of reinforced plastics, we cannot regard only by the cost characteristics, since specific technical requirements can determine the necessity of employing appropriate combinations of various reinforcing materials and binders. The principal requirements from economic standpoint must be regarded as the production of articles

with maximum technical characteristics at minimum possible outlays, with reference to long-term service.

An example of the effective use of glass-reinforced plastics in structures of chemical equipment is their employment to build prefabricated-distributing facilities in filters for the chemical purification of water. Instead of the corrosion-resistance steel prefabricated-distribution facilities employed, structures made of AG-4S glass-reinforced plastic were proposed in the form of "dummy" bottoms fabricated, depending on the diameter, in one piece or fabricated in several sectors.

Technical-economic calculations made for two type classes (diameters of 700 and 1400 mm) showed that the main advantages of using "dummy" bottoms made of AG-4S glass-reinforced plastic lie in the reduction of outlays for installation, lowered consumption of power and regenerating solutions, increased service life of the facilities, and, especially, reduced material expenditures for repair work and replacement of pre-fabricated-distributing facilities that have malfunctioned.

## CONCLUSIONS

In this book the authors attempted, as material was presented, to emphasize the idea that in solving the problem of employing laminated plastics, as well as any plastics in general, in a given structure of chemical equipment one needs a strictly individualized approach from design, operating, and economic points of view. Success can be achieved only when there is a precise determination of the functions fulfilled by the material in the structure of the chemical equipment and with estimates of material's serviceability corresponding to the equipment's parameters. Therefore, with a single methodological approach to estimating the properties of materials for the same parameters one can never obtain full information on the potentialities of a material.

Plastics used in structures of chemical equipment can be classified into four groups by their service designation and thus we can determine characteristic conditions of their service and single out the main parameters for estimating a material's serviceability.

1. The material fulfills the function of a protective coating (for example, sheathing and lining) not experiencing considerable mechanical stresses. In this case it is affected by the medium and temperature. As a result of a temperature change, internal stresses and strains can be induced in the material. The main parameters for estimating the serviceability of a plastic include permeability (the coefficient of diffusion) and heat resistance, as well as creep and longevity with stress relaxation.

2. A plastic serves the role of structural material insulated from contact with the corrosive medium (for example, glass-reinforced plastics lined with thermosetting plastics). In these conditions, the material experiences mechanical stresses and temperature.

The main parameters determining the serviceability of plastics under given conditions include their longevity and creep in atmospheric conditions at different temperatures and mechanical loads. In terms of chemical equipment, these are the mildest conditions of service, since the material is not exposed to a corrosive medium. It must be noted that most studies of plastics, in particular, glass-reinforced plastics, were conducted

precisely for these conditions, and the literature makes available extensive data on the mechanical properties of plastics. It must be remembered that to ensure reliability and longevity of a structure as a whole, we need information on properties of the cladding layer made of thermosetting plastics — its resistance in a given medium and its protective properties (permeability).

3. A plastic serves as a structural material for the fabrication of internal elements of equipment or individual parts of machines in contact with a corrosive medium, but here the plastic's permeability does not play a role. The material is exposed to the medium, mechanical loads, and temperature. Therefore, the parameters for estimating its serviceability include longevity and creep in the given medium at different temperatures and mechanical loads.

4. The material is used in fabricating various shells functioning under pressure (equipment and pipelines). In these conditions it experiences simultaneous exposure to mechanical loads and temperatures with one-sided contact with a corrosive medium. Here we must estimate the longevity and creep in this specific corrosive medium. Additionally, we must obtain data on the gas-tightness of the material and how permeable it is to the medium.

Thus, in the parametric evaluation of plastics, different test methods must be used in accordance with the classification just given (cf Chapter Three), by having the experimental conditions approximate service conditions.

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б8

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